H. Magnesium Powertrain Cast Components (AMD 304[i])

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Objective

- Demonstrate and enhance the feasibility and benefits of using magnesium (Mg) alloys in place of aluminum (Al) in structural powertrain components, thereby achieving at least 15% mass reduction of the cast components.

Approach

- Identify, benchmark, and develop a design database of the potentially cost-effective, high-temperature Mg alloys and, using this cast-specimen database, select the alloys that are most suitable for the Mg components. (Task 1)
- Design, using finite-element analysis (FEA), an ultra-low-mass engine containing potentially four Mg components (cylinder block, bedplate, structural oil pan, and front engine cover) using the most suitable low-cost, recyclable, creep- and corrosion-resistant Mg alloys. (Task 2)
- Create a cost model to evaluate alloy, manufacturing, and technology costs to predict the cost-effective performance of the engine. (Task 2)
- During the execution of Tasks 1 and 2, identify and prioritize the critical gaps in the fundamental science of Mg alloys and their processing that are barriers either to the progress of the project or to the use of Mg in future powertrain applications. Seed-fund the most critical research, and promote additional identified needs to support further development of the Mg scientific infrastructure in North America (NA), thereby enabling more advanced powertrain applications of Mg. This will be one aspect of the technology-transfer deliverables of the Magnesium Powertrain Cast Components (MPCC) project. (Task 3)
- Note that before addressing Tasks 4–6 and funding Task 3 research, an in-depth review of the engine design, including performance and durability predictions, alloy requirements and measured alloy properties, cost model, and predicted mass reduction was be conducted. Passing this gate review was necessary for entry into the second half of the project, which has the goal of demonstrating/validating the engine design with respect to castability, manufacturability, performance, durability, and cost.
- Refine the engine component designs as necessary (updating to match the properties of the alloy selected for each component), design and build tools and patterns, and cast the engine components. (Task 4)

- Excise specimens from the cast components and develop a full mechanical and corrosion design database for the alloys. Create an original equipment manufacturer (OEM)—common material specification for Mg powertrain alloys. (Task 5)
- Assemble complete powertrains, dynamometer-test the components, and conduct end-of-test teardowns. Refine the cost model to support determining the cost-effective performance of the engine. (Task 6)

Accomplishments

- In the years 2001-2004, Tasks 1 and 2 were completed. A successful gate review for entering Phase II was accomplished, involving (1) the selection of alloys for each Mg engine component and revision of the component designs based on the properties of the selected alloys, (2) the issuance of contracts to project teams for tooling and casting each component, and (3) the selection of five basic-research projects in support of the objectives of Task 3.
- In 2005, substantial progress was made to accomplishing the objectives of Task 4, with the completion of component tooling design and build and the initiation of casting trials to produce the cylinder block, the structural oil pan, the front engine cover, and the rear seal carrier.
- The 2006 accomplishments follow.
- The prototype casting development phase for the cylinder block was completed. Fonderie Messier (a division of Honsel, Inc.), in Arudy, France successfully cast Australian Magnesium Technologies alloy SC-1 into sound (leak-free) cylinder blocks using low-pressure sand casting. With the close of the 2006 fiscal year, the casting of "production" cylinder blocks was commenced. This significant success leads the way to full engine testing of the Mg-intensive engine in early 2007.
- Structural oil-pan castings were completed. Spartan Light Metal Products high-pressure die-cast the pans using Dead Sea MRI 153M alloy. After machining and leak testing, the castings were then delivered to Hitachi America for friction-stir welding (FSW) of the cover onto the oil pan reservoir.
- The feasibility of FSW the cover onto the oil pan reservoir was demonstrated. This success validated the project plan to simplify the tooling for the structural oil pan by removing nine bolts hole/flange sets and contributed to being able to cast this very difficult part.
- The front engine-cover castings were completed by high-pressure die casting them at Interment using the Dead Sea MRI 230D alloy. These parts were machined and delivered for engine testing.
- The rear seal carriers were successfully thixomolded by Thixomat using Dead Sea MRI 153M alloy. This is the fourth of the four Mg components designed and cast in the project of the Mg-intensive engine.
- The wear-resistant coating to be used in the engine cylinder bores passed the honing adhesion test. This success was critical for the project strategy of using coatings, rather than liners in the bores.
- Coolant corrosion testing was completed to select a coolant for engine testing. The coolant selected demonstrated improved corrosion inhibition with the Mg cylinder block for both heat-rejecting surface conditions and galvanic corrosion.
- Of the five basic-research projects in support of the Task 3 objectives, which were launched in previous years, one was completed (Computational Thermodynamics and Phase Equilibria - Penn State University) and the other four are making good progress: Hot Tearing Susceptibility - CANMET; Creep Mechanisms - the University of Michigan at Ann Arbor; Corrosion and Corrosion Mechanisms to the Universities of Michigan at Dearborn and Ann Arbor; and Recycling of Creep-Resistant Alloys - Case Western Reserve University.
- The patent application for the structural details of the Mg cylinder block remains in prosecution at the U.S. Patent and Trademark Office (USPTO).

Future Direction

- Complete casting and machining of the cylinder block, conduct sub-assembly of Mg components, with documented machining observations for each of the Mg components to comprehend any potential differences between the chosen Mg alloys and Al.

- Excise specimens from cast Mg engine components and test to create an excised-specimen property database of the three selected Mg alloys, which will complement the cast-specimen database completed during Phase I.
- Complete assembly and dynamometer testing, teardown, and analysis of the Mg-intensive engines.
- Input data from all stages of the manufacture of the die-cast oil pan and front engine cover and the sand-cast cylinder block into the cost model to determine the cost-effective performance of the Mg-intensive engine.
- Complete the four remaining basic-research projects to their respective completion dates.
- Complete the project by September 30, 2007.

Introduction

The use of Mg alloys to reduce the mass of automotive components has grown rapidly. NA parts include instrument panels, cross-car beams, seat frames, steering wheels, intake manifolds, valve covers, transfer cases, numerous small brackets and, most recently, the Mg engine cradle for the Z06 Corvette. In Europe, Mercedes-Benz has introduced an automatic transmission case and BMW has introduced a unique, inline, 6-cylinder engine. The BMW "composite" engine comprises an Al-alloy inner casting around which is cast a Mg shell. The Al "inner" provides the performance requirements such head bolt threads, structural stiffness, and housing the engine coolant. What remains to be determined is the feasibility of an all-Mg cylinder block.

The Magnesium Powertrain Cast Components (MPCC) Project was organized to realize the vision of a Mg-intensive engine (with an all-Mg cylinder block) that is cost-effective, light weight, and meets the manufacturability and durability requirements of the automotive industry.

To determine the feasibility of the Mg-intensive engine, MPCC Project team redesigned a V6 engine from Al to Mg. The engine chosen was the 2.5/3.0L Ford Duratec, which is shown in Figure 1. A production engine was chosen in order to allow production parts such as the valve train to be used without modification. While this limited the design freedom for the Mg-intensive engine, the economics of the "green field approach" were prohibitive.

Designing a V block in itself was a significant technical reach for Mg, relative to an in-line block because through-bolting could not be used.

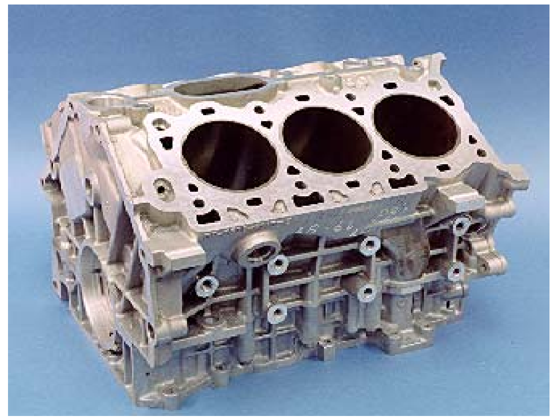

Figure 1. Production V6 Duratec block and bedplate.

Additional technical challenges anticipated included having structural stiffness, stability and durability at the operating temperature; cooling the engine with non-corrosive coolant and preventing galvanic corrosion due to fasteners and gaskets; and selecting a suitable bore/piston/ring system.

Though initially intended to contain four Mg components: the cylinder block (CB), the bedplate, a structural oil pan (SOP), and the front engine cover (FEC), the final design became that of a deep-skirt block without a bedplate.

The MPCC project was launched in January 2001 and implemented in two phases. In Phase I, the engine design was completed based on available alloy property data and used to determine the alloy property requirements for each Mg component. Additionally, several high-temperature Mg alloys were cast and tested to identify those that would be most suitable for the engine components. In October 2003, the project team conducted a successful review of its Phase I deliverables and subsequently launched Phase II, the completion phase of the project.

The main objective of Phase II is to validate the Mg-intensive engine design by casting the parts and conducting engine tests. The CB, SOP, FEC and the rear seal carrier (RSC) have been cast and engine testing is anticipated in early 2007. The other major Phase II objective is to launch and complete projects in critical basic research for advanced Mg powertrain applications. Research in these areas will strengthen the infrastructure for Mg research in NA, thus contributing to the realization of Mg-intensive powertrains.

The MPCC project team will complete the project in September 2007. This is later than originally planned because of the time required to solve the design challenges for the Mg CB which were due to the high coefficient of thermal expansion (CTE) of Mg (the solution resulted in a patent application) and difficulty in casting sound components, in particular the CB. Progress was hard, but in 2006 success was achieved for casting all of the Mg components.

Engine Components

The mass-reduction target set by the MPCC project team was 15% for the cast Mg components. The final design achieved a much greater mass reduction. The final design contains the following Mg components: the cylinder block (CB), the structural oil pan (SOP), the front engine cover (FEC), and the rear oil seal carrier (RSC). It also contains cast-iron crank bore inserts and bearing caps. A description of each component and the progress made toward tooling design, build, and casting follows.

Cylinder Block: The Mg CB is based on the Al 3.0 liter (L) block, but with bore diameters corresponding to a 2.5 L. This increase in cylinder wall thickness reduced bore distortion. The Al CB and bedplate was replaced by a deep-skirt CB and no bedplate. Bearing caps were bolted to the crank bore inserts in the CB bulkheads, see Figure 2.

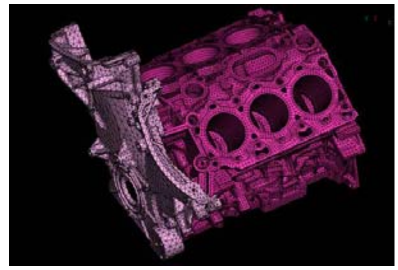

Figure 2. The Mg-intensive design: block and front engine cover.

Fonderie Messier, in Arudy, France is low-pressure casting the Mg CB using SC-1, a sand-casting alloy produced by Australian Magnesium Technologies. The block is cast in pan-rail up position with cast-in-place pearlitic ductile-iron crank bore inserts.

Three dozen "prototype" castings were made in the course of developing the gating and runner system and tuning the casting parameters. The major casting challenges were shrinkage and gas defects in the main oil gallery and the clean-oil line. These were eliminated but some cosmetic weld repair is necessary.

Sound "prototype" CB's (passed X-ray inspection and post-machining leak testing) were achieved at the end of 2006. Thirty "production" castings are being produced in support of the engine test program. A partially-machined casting is shown in Figure 3.

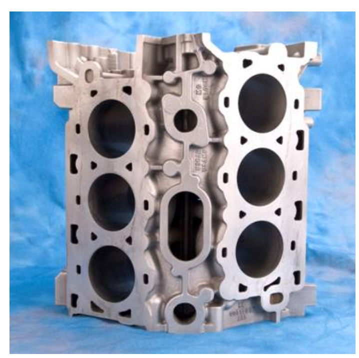

Figure 3. Partially- machined Mg block.

Cylinder-Block Bore Treatment: The MPCC strategy for the cylinder bores is to use a wear-resistant, thermal-spray coating. Successful adhesion test results were obtained. Honing development is progressing using "prototype" CBs. These were bored and the bores were prepared for coating by a roughening treatment. It is necessary that the "production" blocks do not have pinhole porosity of the type shown in Figure 4 lest it interfere with the quality of the coating.

Coolant Selection: Selection of the coolant for engine testing has been completed. Four coolant formulations, one from each of the major coolant suppliers, were tested with SC-1, the CB alloy. The coolants were developed by suppliers based on the results obtained in the first round of coolant testing, during Phase I of the project.

On the basis of the double-blind test results shown in Figure 5, coolant 2 was selected for the engine tests. All of the Phase II coolants performed better than the Phase I coolant formulations in the ASTM D4340 hot-surface corrosion and ASTM D1384 galvanic-corrosion tests. Mg still corroded in the best coolant somewhat more than Al did in the same test. The corrosion behavior of Mg alloys continues to be a high-priority research area: see Task 3 research.

Head Gasket: Dana Corporation designed the head gasket for the Mg engine. The 3-layer design contains a wave stopper sandwiched between the two active layers. The final-design materials and geometry are the result of FEA simulation for 100% and 70% bolt load cases at assembly and operating conditions. The load distribution is good, but fine tuning of the sealing pressure remains to be done. Analysis with steady-state temperature maps is in progress.

Figure 4. Pinhole porosity exposed by boring.

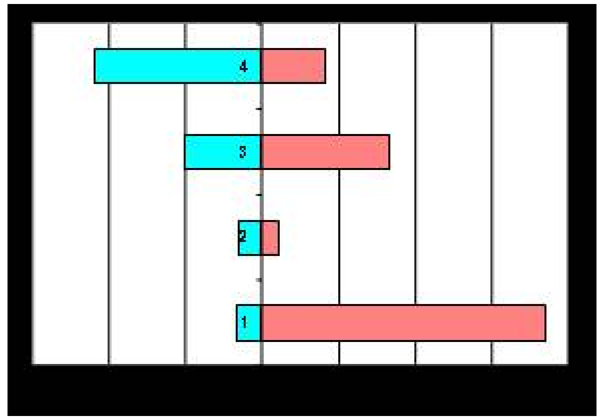

Figure 5. Corrosion results for D4340 (left) and D1384 (right) showing that coolant 2 has the best overall performance.

Structural Oil Pan: High-pressure die casting the SOP was a major challenge. Several separate casting trials were required by Spartan Light Metal Products to obtain sufficient quality castings for engine testing and component testing. The tooling for the die was built by HE Vannatter using Spartan gating, both designs being based on simulations done by Technalysis. The casting difficulty was due to the complex geometry of this component, in particular, the sump and the slides needed for it, the arrangement and size of the ribs, and the solidification behavior of the alloy, Dead Sea Magnesium MRI 153M. Hot cracking and cold shuts were eventually eliminated after altering the die. Nevertheless, the castings were impregnated to pass leak testing. The final mass of the SOP is significantly less than its Al counterpart. A schematic of the structural oil pan is shown in Figure 6.

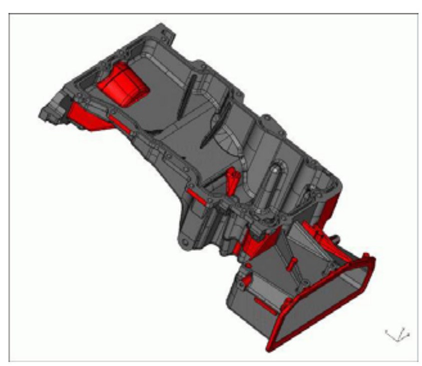

Figure 6. Schematic of Mg structural oil pan.

The sump cover of the Al production version of the oil pan is attached with eleven bolts. These were removed in the Mg design to simplify casting. Hitachi North America successfully friction-stir welded the cover in place. The use of friction-stir welding is one of several fastening methods used in various parts of the MPCC engine. The Al and Mg designs are shown in Figure 7.

Figure 7. SOP sump covers: Al production (with bolts) and Mg design (without).

Front Engine Cover: This part was high-pressure die cast by Intermet using a die built by Exco Engineering. The major redesign focus of the FEC was its noise, vibration and harshness (NVH) performance. The alloy used for the FEC is Dead Sea MRI 230D.

The cast parts showed some hot cracking. As with the SOP, hot cracking was minimized by changing the gating system and casting conditions. Other changes made to the tooling also contributed. The castings have been completed, machined and are awaiting engine testing. The FEC is shown in Figure 8.

Rear Oil Seal Carrier: The Mg version of the V-6 engine requires the use of a rear oil seal carrier. These parts were thixomolded by Thixomat. The alloy chosen was Dead Sea MRI 153M, the same alloy as being used for the SOP. The first casting trials showed hot cracking, but subsequent changes to the die were made, which resulted in RSCs with excellent quality. They are awaiting engine testing. An RSC is shown in Figure 9.

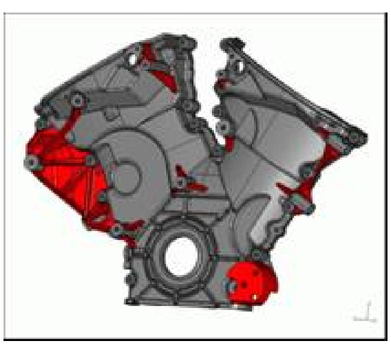

Figure 8. The Mg front engine cover design.

Figure 9. Mg rear oil seal carrier cast by Thixomat.

Engine Dynamometer Test Program

Engine testing is the ultimate measure of the technical readiness of Mg for powertrain applications. The MPCC test program was developed to validate the engine design and its predictions about the durability and NVH performance of the engine.

The test program is based on that used for the Al Duratec. Seven tests comprise the plan. Engine teardown analysis is part of the test program. The engine tests are:

- Piston Skirt Marking
- Hot Scuff and Cold Scuff
- 150 hour deep thermal
- 300 hour high-speed durability
- 480 hour key life thermal
- 675 hour engine system test

Mechanical Property Testing and Database Development

The database architecture to house the property testing from Phase I of the project has been completed. The data that were generated in Phase I were used to select the alloys for each engine component and for design revisions. The database architecture was developed at Westmoreland Mechanical Testing & Research. Consistent with the original objective of the project, the MPCC database and the Structural Cast Magnesium Development (see 2.G) database are of common architecture. The two databases are being combined.

The alloy property data that were produced in Phase I of the project were obtained from cast specimens. The Phase II data will come from specimens excised from the cast components. This testing began in 2006.

Task 3. Critical Scientific Needs for Powertrain Magnesium Alloys

During Phase I of the MPCC project, gaps in the science of powertrain Mg alloys and/or processing were identified and documented. These gaps are critical for future applications of Mg in automotive powertrains. It was an original objective of the MPCC project to identify such gaps and to start new, or expand existing, research in NA to address them. Five projects were launched and one has been completed. The others will be completed in 2007.

Computational Thermodynamics and Alloy Development of Magnesium Alloys: Prof. Z.K. Liu at Penn State University uses first-principles calculations to compute thermodynamics databases. They are used to predict phase equilibria in critical alloy systems including Mg-Al-Ca and Mg-Ca-Sn. An example of results from this project, the Ca-Sn binary was predicted from *ab initio* calculations and compared with experimental work from the literature. The predicted phase diagram is shown in Figure 9. This project is complete.

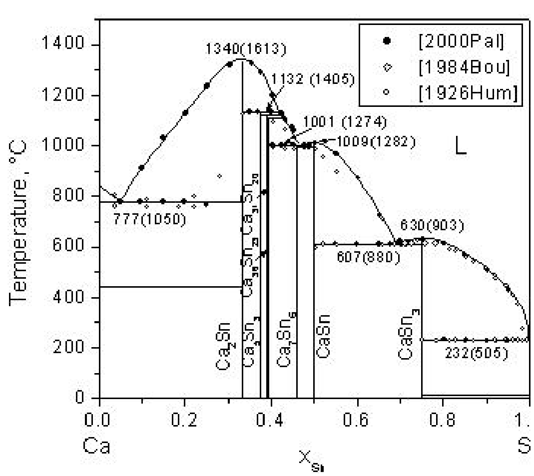

Figure 9. Calculated Ca-Sn binary from *ab initio* calculations.

Hot-Tearing Behavior of Magnesium Alloys: Dr. D. Emadi at CANMET seeks (1) to optimize an experimental system for quantifying the hot-tearing susceptibility of Mg alloys and (2) to determine the microstructural basis for hot tearing in these alloys. Hot tearing is related to the solidification behavior of the alloy and the tendency of a particular alloy to hot tear has a large impact on its castability and the economics of the casting process. Hot tearing or hot cracking was an issue for each of the components that were cast in the MPCC project. The Mg-Al alloys being studied contain Ca and Sn. Dr. Emadi's effort addresses the impact of these alloying elements on the hot-tearing behavior of AM50 under sand-casting conditions.

Creep, Bolt-Load Retention, and Microstructural Analysis of High-Temperature Mg Alloys: Creep is perhaps the single most important requirement for Mg alloys for use in powertrain applications. Creep is the slow plastic deformation of a material subjected to sustained load at high-temperature. Prof. W. Jones' team at the University of Michigan at Ann Arbor is developing mechanistic models and seeking the microstructural basis for the observed creep rates of the high-temperature alloys under tensile creep or compressive/bolt load conditions. The bolt-load retention system is shown in Figure 10.

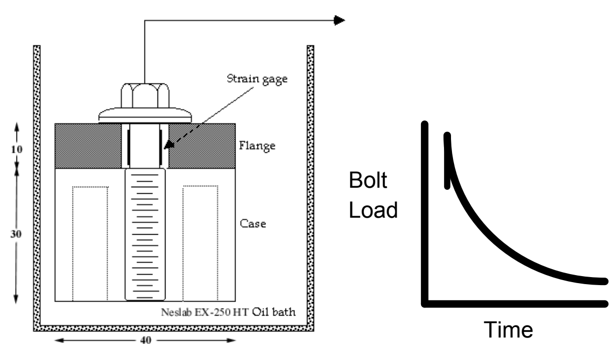

Figure 10. Bolt-load retention testing showing test assembly and typical change in bolt load with time at test temperature.

Evaluation of Mg Corrosion by Various Methodologies and Surface Composition of Magnesium Alloys by Rutherford Backscattering: The first phase of this project was begun at the University of Michigan at Dearborn under the leadership of Prof. P.K. Mallick. All of the high-temperature Mg alloys considered in the MPCC project were corrosion tested using several different methodologies. The differences observed among the methods were documented and extensive research was conducted to explain the differences on the basis of the operating corrosion mechanisms. The experimental configuration for simultaneously monitoring several corrosion measurement methods is shown in Figure 11. In the second phase of the work, Rutherford Backscattering (at the University of Michigan at Ann Arbor) will be used to study the corrosion interface to further reveal the microstructural basis for Mg corrosion. The results of this work will contribute to the development of improved alloys and/or improved corrosion mitigation strategies.

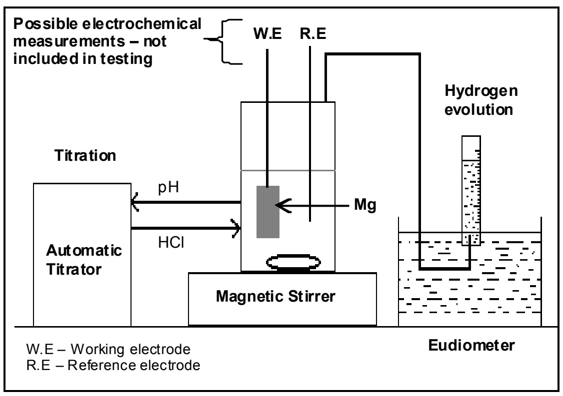

Figure 11. The simultaneous corrosion test system.

Fluxless Recycling Methods and Process Control for Creep-Resistant Magnesium Alloys: Prof. D. Schwam at Case Western Reserve University and E. Es-Sadiqi at CANMET. Recycling of current automotive Mg alloys is well understood. However, the creep-resistant alloys contain alloying elements such as Ca, Sr, Sn, and rare earths. These elements are not amenable to current flux-based recycling methods because they react with the flux. The significance of this on the practice and economics of recycling has yet to be determined. The first phase of this project produced an in-depth survey of the industry and the scientific literature to determine the recycling barriers. The second phase of the work will be research to further overcome the identified barriers.

Conclusion

The MPCC Project has made excellent progress since its inception in 2001. Project accomplishments include completion of the component designs, building and testing of the component dies, and casting the parts for use in engine dynamometer testing.

In accomplishing this work collaboratively, the MPCC project enabled sharing the costs and risks and avoided duplication of effort. It has already renewed interest in using Mg in automotive powertrains within the Mg supplier and manufacturing community as well as the automotive industry. The project is promoting greater competition and rapid development of Mg sources, manufacturing capability, and engineering expertise, and has already encouraged the development of scientific research projects into the properties, processing, and behavior of Mg at various universities and national laboratories in NA. The project team expects to complete all “bill of materials” aspects leading to the initiation of engine dynamometer testing in 2007.

Presentations/Publications/Patents

1. J.A. Hines, R.C. McCune, J.E. Allison, B.R. Powell, L.J. Ouimet, W.L. Miller, R.S. Beals, L. Kopka, and P. P. Ried, “Building a Mg-Intensive Engine: A Progress Report on the USAMP Magnesium Powertrain Cast Components Project,” 2006 Magnesium Technology Symposium of TMS, San Antonio, Texas, March 12, 2006.

2. R. Arroyave, M. Ohno. R. Schmidt-Fetzer, and Z.K. Liu, “Finite-Temperature Thermodynamic Properties of Intermetallics in the Mg-Ca-Sn System via First-Principles Methods,” 2006 Magnesium Technology Symposium of TMS, San Antonio, Texas, March 12, 2006.

3. B.R. Powell, L.J. Ouimet, G.K. Tappen, J.E. Allison, J.A. Hines, R.C. McCune, R.S. Beals, L. Kopka, and P. P. Ried, “The USAMP Magnesium Powertrain Cast Components Project,” 17th Annual Magnesium in Automotive Seminar of the International Magnesium Association, Livonia, MI, April 27, 2006.

4. B.R. Powell, W.L. Miller, L.J. Ouimet, J.A. Hines, R.M. McCune, and J.A. Allison, R.S. Beals, L. Kopka, and P.P. Ried, "The USAMP Magnesium Powertrain Cast Components Project," Proceedings of the Global Powertrain Congress, Novi, Michigan, September 20, 2006.

5. R. Arroyave, M. Ohno. R. Schmidt-Fetzer, and Z.K. Liu, "Finite-Temperature Thermodynamic Properties of Intermetallics in the Mg-Ca-Sn System via First-Principles Methods," Proceedings of the 2006 Magnesium Technology Symposium of TMS, San Antonio, Texas, March 12, 2006, pp. 429-434.

6. B.R. Powell, W.L. Miller, L.J. Ouimet, J.A. Hines, R.M. McCune, J.A. Allison, R.S. Beals, L. Kopka, and P.P. Ried, "The USAMP Magnesium Powertrain Cast Components Project," Proceedings of the 2006 Global Powertrain Congress, ed. Nasim Uddin, Novi, Michigan, 36 pp. 43-50 September 19-21, 2006.

7. R.J. Natkin, B. Oltmans, T.J. Heater, J.E. Allison, J.A. Hines, G.K. Tappen, and D. Peiskammer, "Crank Shaft Support Assembly," Utility Patent Application 11/373,544 filed March 10, 2006.

Acknowledgments

The success of this project is due to the dedicated efforts of a large number of team members at Ford, DaimlerChrysler, and General Motors. The many other companies and organizations making up the project team are listed in Table 1.The continuing support of our respective companies and the US Department of Energy is gratefully acknowledged.

Table 1. The MPCC Project Team.

Product Design:	Ford, GM, DCX, Magna Powertrain
Alloy Suppliers:	AMC, Dead Sea Magnesium, GM, Noranda, Norsk-Hydro, Solikamsk, VSMPO-Avisma
Casters:	Eck, Gibbs, Intermet, Lunt, Meridian, Nemak, Spartan, Thixomat
Bore Treatment:	Gehring, Flame Spray
Tooling:	Becker, Delaware, EXCO, HE Vannatter
Coolants:	Ashland/Valvoline, ChevronTexaco, Honeywell/Prestone, INTAC/CCI
Fasteners:	RIBE
Gaskets:	Dana/Victor Reinz
Testing Labs:	Amalgatech, CANMET, Stork CRL, Quasar, Westmoreland Mechanical Testing & Research
Casting Modeling:	EKK, Flow Science, MAGMAsoft, Technalysis
Professional Organizations:	IMA, NADCA
Project Administration :	Ried and Associates

[i] Denotes project 304 of the Automotive Metals Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.