H. Magnesium Powertrain Cast Components

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Objective

- Demonstrate and enhance the feasibility and benefits of using magnesium alloys in place of aluminum 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 magnesium alloys and, using this cast-specimen database, select the alloys that are most suitable for the magnesium components. (Task 1)
- Design, using finite-element analysis (FEA), an ultra-low-mass engine containing potentially four magnesium components (cylinder block, bedplate, structural oil pan, and front engine cover) using the most suitable low-cost, recyclable, creep- and corrosion-resistant magnesium 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 magnesium alloys and their processing that are barriers either to the progress of the project or to the use of magnesium in future powertrain applications. Seed-fund the most critical research, and promote additional identified needs to support further development of the magnesium scientific infrastructure in North America, thereby enabling more advanced powertrain applications of magnesium. 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 will be conducted. Passing this gate review is 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 magnesium 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 magnesium 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. The 2005 accomplishments follow.
- Completed the cylinder-block design using properties of the Australian Magnesium Technologies alloy SC-1 and issued a contact for low-pressure sand casting the magnesium block to Fonderie Messier (a division of Honsel, Inc.), in Arudy, France. This was a critical accomplishment following a 2004 fire at the Eck Industries foundry and the decision by Denison Industries that casting the cylinder block would be too great a challenge for their capability.
- Tooling design and build were completed by Becker CAD CAM CAST for the cylinder block and eight prototype castings were made during the reporting period at Fonderie Messier using gating developed with EKK and MAGMAsoft simulation software.
- Filing of a patent application for the structural details of the magnesium cylinder block was approved by the USAMP leadership and in process.
- The structural oil pan tooling design and build were completed by HE Vannatter using properties of Dead Sea MRI 153M alloy. Casting trials were performed by Spartan Light Metal Products using gating designs based on casting simulation by Technalysis. The combination of limited available gating area and the solidification behavior of the alloy have made this a difficult component to cast. Ongoing changes have improved the castings, but at reduced mass savings.
- The front engine cover tooling design and build were completed by EXCO and Extech using properties of the Dead Sea MRI 230D alloy. The components were cast by Intermet and, as in the case of the oil pan, required fine tuning of the gating system and casting conditions to produce sound castings.
- The rear seal carrier tooling design and build were completed by PCMI using properties of Dead Sea MRI 153M alloy. The component is being produced via thixomolding by Thixomat.
- Completed the first phase of adhesion tests for a wear-resistant coating to be used in the engine cylinder bores. Several surface preparations and two coating deposition methods were evaluated with excellent adhesion to magnesium being demonstrated.
- Made further improvements to the architecture for the magnesium alloy property database, including adding thermophysical and fatigue properties. Began working with the Structural Cast Magnesium Development project (see report 2.G) team for distribution of the combined databases.
- Launched five basic research projects in support of the Task 3 objectives: (1) Computational Thermodynamics and Phase Equilibria to Penn State University; (2) Hot Tearing Susceptibility to CANMET; (3) Creep Mechanisms to the University of Michigan; (4) Corrosion and Corrosion Mechanisms to the Universities of Michigan at Dearborn and Ann Arbor; and (5) Recycling of Creep-Resistant Alloys to Case Western Reserve University and CANMET.

Future Direction

- Complete casting, machining, and sub-assembly of magnesium components, with documented machining observations for each of the magnesium components to comprehend any potential differences between the chosen magnesium alloys and aluminum.
- Excise specimens from cast magnesium engine components and test to create an excised-specimen property database of the three selected magnesium alloys, which will complement the cast-specimen database completed during Phase I.
- Complete assembly and dynamometer testing, teardown, and analysis of the magnesium-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 magnesium-intensive engine.
- Continue monitoring and reviewing the five basic research projects to their respective completion dates.
- Deliver final reports for the project by June 30, 2006.

Introduction

Since launch in 2001, the Magnesium Powertrain Cast Components (MPCC) project team has been working toward the ultimate goals of determining and then demonstrating the readiness of magnesium (Mg) alloys to be used to reduce the mass of automotive powertrains. The project team exceeded their 15% mass reduction target for the Mg-intensive engine, selected alloys for each Mg component, and completed the engine component design revisions using the respective properties for each selected Mg alloy. In FY 2005 the following milestones were accomplished: (1) tooling for each of the four Mg engine components was designed and built, (2) initial casting trials were completed and good progress was made to achieving sound parts for both engine testing and the excised specimen database, and (3) all five research projects in the critical areas, as identified by the project team, were launched. In addition, good progress was made developing the bore treatment for the cylinder block and for selection of the coolant to be used during the engine dynamometer testing.

The Magnesium Engine Components

The magnesium-intensive V-6 engine design was based on the aluminum 2.5/3.0L Ford Duratec engine. The final design (using the selected alloy properties for each component) resulted in overall mass reduction that significantly exceeded the original 15% target set by the MPCC project team. The major MPCC project activity in FY 2005 was to design and build tooling for casting each of the four magnesium components. This was accomplished and casting trials of all of the components were begun, with varying degrees of success. Nevertheless, it is expected that all of the parts will be cast and machined within the timing required to begin engine testing.

Cylinder Block: The Australian Magnesium Technologies alloy SC-1, a sand-casting alloy, was selected for this component. Prior experience (MPCC Project Phase I) with this alloy indicated that it would be necessary to use low-pressure casting, rather than gravity casting to produce sound parts. When it became apparent that neither Eck nor Denison Industries had the capability to do this, the project team contracted Fonderie Messier (a division of Honsel) to cast the cylinder blocks. The gating design was developed using casting simulations by MAGMAsoft and EKK. The tooling was designed and built by Becker CAD CAM CAST. The use of thermocouple-instrumented molds to validate the gating design and the solidification behavior of the castings also contributed to the rapid progress that Fonderie Messier is making.

Fonderie Messier cast the block pan rail up in a completely closed system to enable mold purging. Chills and crank-bore inserts were incorporated into the mold and the inserts were successfully cast-in-place. Excellent insert/Mg interface integrity was observed and this integrity was maintained even after heat treating. Some porosity has occurred in the thick regions of the casting but this is being addressed by use of chills and additional risers.

Figure 1 shows the as-cast block from which the risers and gating having been removed.

Structural Oil Pan: The Mg alloy chosen for this component was Dead Sea MRI 153M. The major changes to the final design of this component were made to address "noise, vibration, and harshness" (NVH) issues, particularly with respect to the sump area of the oil pan; see Figure 2. It is required that the Mg-intensive engine equal the performance of the Al engine. Accordingly, the NVH concerns were addressed by adding ribs to increase stiffness. In other areas of the casting, material was removed to minimize mass, generally reducing the wall thickness from 3.5 to 2.5 mm.

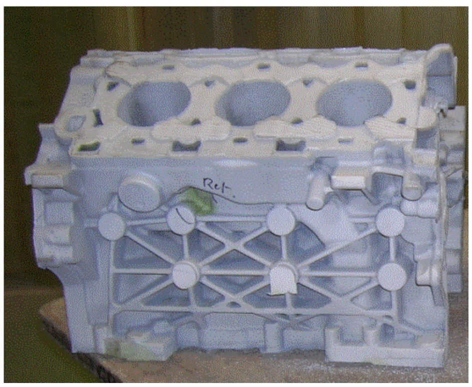

Figure 1. The Mg cylinder block, as cast at Fonderie Messier.

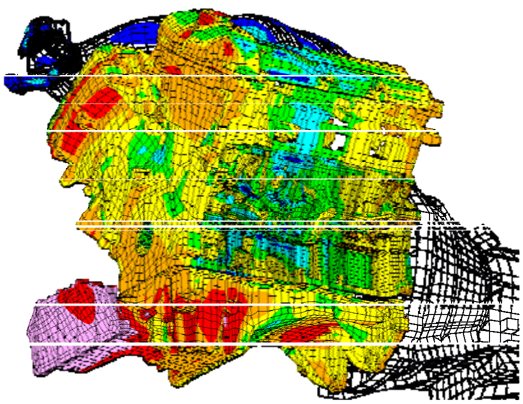

Figure 2. NVH analysis of the Duratec engine. Note the acoustic intensity of the oil pan sump.

The tooling for this high-pressure die casting was designed and built by HE Vannatter and the gating was designed by Spartan LMP using the simulations done by Technalysis. Unfortunately, the oil pan has been very difficult to cast for the following reasons: the complex geometry of this component, in particular, the sump and the slides needed; the arrangement and size of the ribs; and the solidification behavior of the alloy. As a result, the die has been evolving over the course of several casting trials. These changes include increasing the wall thickness in critical areas and changing the number of ribs, their locations, and sizes. Castings are being made, but these will require repair for hot cracking, so further die changes are being considered.

The cover for the sump will be a friction-stir-welded (FSW) plate. The use of FSW enables further mass reduction and part simplification by eliminating the attaching bolts. FSW will be done by Hitachi-North America.

Front Engine Cover: The major redesign focus of this component, like that of the oil pan, was NVH performance. Interestingly, the NVH model predicted that wall thinning will not adversely affect NVH performance if additional ribs are used in critical areas.

The alloy chosen for this part is Dead Sea MRI 230D even though the creep resistance of this alloy is greater than needed for the application. The MPCC team did this because they wanted to evaluate a very-high-creep-resistant alloy in anticipation of a high-pressure die-cast (HPDC) cylinder block. In this sense, the front engine cover is serving as a surrogate for the HPDC cylinder block. The tooling for the front engine cover was designed and built by EXCO and Extech. The casting was done by Intermet. The cast parts showed some hot cracking. As was done with the oil pan, preventing hot cracking required increasing the gate area, fine tuning of the shot profile, and reducing the dwell time. Also, radii were softened and texturing was used to facilitate metal flow. The castings are currently being leak tested and sorted for delivery to the machining site. The front engine cover is shown in Figure 3.

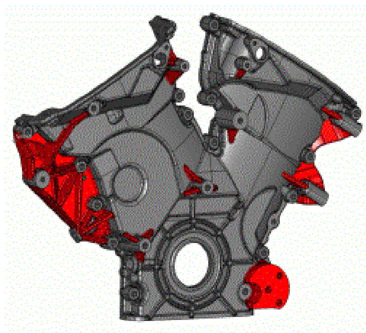

Figure 3. The Mg front engine cover.

Rear Oil Seal Carrier: The Mg version of the V-6 engine requires the use of a rear oil seal carrier, as shown in Figure 4. The Thixomat thixomolding process was used to achieve this near-net-shape part. The alloy chosen is Dead Sea MRI 153M, the same alloy as being used for the oil pan. As a result of the first casting trials, some changes to the die are being made and parts are expected to be ready when required.

Engine Bore Development

The Al Duratec engine uses iron liners in the cylinder bores. Iron bores were not considered for the MPCC Mg engine; instead, the project team chose to develop a spray-deposited, wear-resistant bore coating. This approach will save mass, enable better heat transfer, and improve block stiffness by allowing thicker bore walls. Thicker walls will reduce bore distortion and provide greater flexibility with respect to designing for creep management and head-gasket sealing. Two deposition processes and a range of surface preparations are being evaluated.

Figure 4. The Mg rear oil seal carrier.

The ASTM C-633 adhesion test has been used to screen the coatings using Mg blocks that were cast in Phase I of the project. The adhesion results have been excellent. A specification for maximum porosity on the bore surfaces to be coated has been incorporated into the requirements that Fonderie Messier has for the cast cylinder blocks. Additional development work will proceed as soon as the prototype blocks have been provided.

Engine Coolant

Four coolants were tested in Phase I for hot-surface corrosion (ASTM D4340) and galvanic corrosion (ASTM D1384) with each of the HPDC and sand-casting alloys. Since selecting SC-1 for the cylinder block, each of the coolant suppliers has been working to improve their coolants with respect to this alloy. Corrosion testing of the new coolants is being done to identify the coolant to be used in the engine dynamometer tests.

An additional coolant test was introduced during Phase II. This test, based on the ASTM D1384 test for galvanic corrosion, was developed by Victor Reinz to determine the durability of the Mg in the vicinity of the head gasket. In this region, an "electrolytic cell" has been created by the system, which comprises the stainless steel head gasket, the Mg cylinder block, the aluminum cylinder head, and the coolant. The sample configuration for this test is shown in Figure 5. The concern being addressed by this test is whether or not transition metals from the gasket will plate out on the Mg, where they will act as cathodic centers and lead to pitting corrosion.

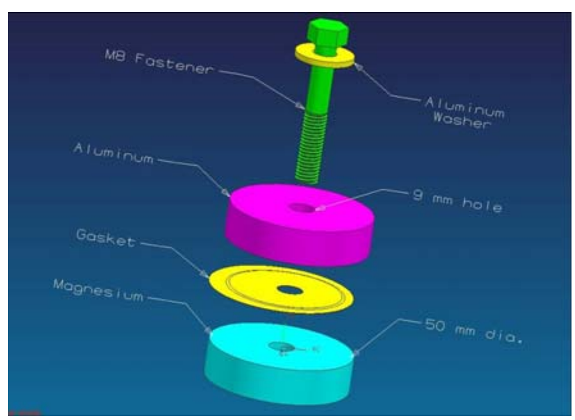

Figure 5. Head-gasket corrosion test assembly.

Test results show that pitting does occur with some metal-coolant combinations. Further testing will be done with the advanced coolants. In addition, coolant samples will be taken during the engine dynamometer tests to detect any corrosion and breakdown, if it occurs.

Engine Dynamometer Test Program

Engine testing is the ultimate measure of the technical readiness of Mg for powertrain applications. The test program was developed to validate the engine design model and its predictions about the durability and NVH performance of the engine. These tests will also help to verify that the selected alloys can be used in production engines. The test program and supporting statement of work were completed and a request for quotes yielded five quotes.

Seven tests comprise the program: (1) hot scuff, (2) cold scuff, (3) deep thermal shock, (4) high speed durability, (5) key life thermal, (6) long-term engine system, and (7) piston-skirt marking. Full engine disassembly and teardown analysis will be performed subsequent to all tests.

Critical Scientific Needs for Powertrain Magnesium Alloys

During Phase I of the project, numerous gaps in the technical understanding of Mg alloys and/or processing were identified and documented. These gaps were determined to be critical for future applications of Mg to automotive powertrains. It was an original objective of the MPCC project to identify such gaps and to either start new or expand existing research in North America that addressed these gaps. The procedure for accomplishing this has been described in the 2004 Progress Report. Five projects were launched in FY 2005.

Computational Thermodynamics and Alloy Development of Magnesium Alloys: Funding was awarded to Z.K. Liu at Penn State University to develop first-principle models for incorporation into computational thermodynamics databases. These models will be used to predict phase equilibria in critical alloy systems including magnesium-aluminum-calcium and magnesium-calcium-tin. Key aspects of this project are the sharing of data and experimental verification of the phase equilibria predictions. The collaborative group has been expanded to include researchers at the University of Michigan at Ann Arbor, the University of Wisconsin, and the Technical University of Clausthal. This interaction is already providing critical review of the Penn State University predictions and the sharing of data is benefiting research collectively and independently.

Hot Tearing Behavior of Magnesium Alloys

Funding for this project was awarded to D. Emadi at CANMET-NRC. His objective is two-fold: (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 has been an issue for each of the components that have been cast in the MPCC project, though in most cases it has been addressed successfully.

Creep, Bolt Load Retention, and Microstructural Analysis of High Temperature Magnesium Alloys: This project was awarded to W. Jones et al., at the University of Michigan at Ann Arbor. Creep is perhaps the single most important requirement for Mg alloys if they are to be used in powertrain applications. Creep is the slow plastic deformation of a material subjected to sustained load at high temperature. The research team will be developing mechanistic models for creep and seeking the microstructural basis for the observed creep rates.

Evaluation of Magnesium 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 P.K. Mallick. In this phase, 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 has been conducted to explain those differences on the basis of the operating corrosion mechanisms. 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.

Fluxless Recycling Methods and Process Control for Creep-Resistant Magnesium Alloys: Funding for this project was awarded to D. Schwam at Case Western Reserve University and E. Essadiqi at CANMET-NRC. Recycling of current automotive Mg alloys is generally well understood. However, the new alloys, those that have the necessary creep resistance for powertain applications, contain additional alloying elements such as calcium, strontium, tin, 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 will be to conduct an in-depth survey of the industry and the scientific literature to determine the scientific and technical barriers to recycling and the progress made to date to address them. The second phase of the work will be research to further overcome the identified barriers.

Conclusions

The MPCC Project has made excellent progress since its inception in 2001. The science and engineering property database for the high-temperature, creep-resistant magnesium alloys which was developed after extensive casting and testing has been combined with the Structural Cast Magnesium Development and the Design for Product Optimization databases of ambient-temperature alloys and is being readied for joint distribution to the respective project teams. The MPCC properties enabled revised engine component designs and the design and build of the tooling to cast the components. Casting is ongoing and it is expected that testing of assembled engines will begin in mid-FY 2006. Documentation of the engine design and cost model to predict cost-effective performance of the Mg-intensive engine and the engine tests will be completed in 2006. The basic research projects begun in FY 2005 will continue beyond the engine test part of the MPCC project into 2007 and, along with successful engine testing, represent the legacy of the MPCC project.

Acknowledgements

The success of this project is due to the dedicated efforts of a large number of team members, in particular, the author's colleagues at Ford, DaimlerChrysler and General Motors. The many other companies and organizations making up the project team were listed in the FY 2003 Progress Report. However, the author would like to acknowledge the MPCC core team for their work: John Allison, Joy Hines, and Robert McCune from Ford; Randy Beals and Lawrence Kopka from DaimlerChrysler; Larry Ouimet, James Quinn, and Grant Tappen and William Miller from General Motors; and Peter Ried from Ried and Associates. The continuing support of our respective companies and the U.S. DOE is gratefully acknowledged.

Presentations/Publications/Patents

1. "Light-Weight Magnesium-Intensive Engine Developments," published in the 2004 FreedomCAR Highlights.
2. "Overcoming the Barriers to the Magnesium-Intensive Engine," B.R. Powell, presented at the joint meeting of the Ohio and Mid-Western Sections of the American Foundry Society and the American Society for Quality Control, Bowling Green, Ohio, February 2, 2005.
3. "The USAMP Magnesium Powertrain Cast Components Project," 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, presented at the 16th Annual Magnesium in Automotive Seminar of the International Magnesium Association, Livonia, Michigan, March 17, 2005.
4. "The USAMP Magnesium Powertrain Cast Components Project: Testing the Magnesium-Intensive Engine," 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, presented at the Magnesium Technologies session of the 2005 Society of Automotive Engineers World Congress, Detroit, Michigan, April 11, 2005.
5. "The USAMP Magnesium Powertrain Cast Components Project: Testing the Magnesium-Intensive Engine," 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, presented at the Achieving Lightweight Vehicles session of the 2005 Society of Automotive Engineers World Congress, Detroit, Michigan, April 14, 2005.

6. "The USAMP Magnesium Powertrain Cast Components Project: Testing the Magnesium-Intensive Engine," 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, presented by R.S. Beals at the 62nd International Magnesium Association International Congress in Berlin, Germany, May 24, 2005.
7. Magnesium Powertrain Cast Components Project," B. R. Powell, presented at the AMD Board Casting Off-Site, USCAR, Southfield, Michigan, September 29, 2005.
8. A patent application is in preparation.