G. Structural Cast Magnesium Development (SCMD - AMD 111[i])

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Contractor: U.S. Automotive Materials Partnership
Contract No.: FC26-02OR22910

Objective

Overcome technical and manufacturing issues (high-integrity castings, corrosion & joining) that limit the lightweighting application of structural cast magnesium (Mg) automotive components. Then, demonstrate the successful application of a magnesium engine cradle in a volume production-type vehicle.

Approach

- Improve the scientific understanding of Mg alloys.
- Develop a cost model that compares cast Mg chassis component costs to other materials and processing techniques.
- Provide comprehensive database and design guidelines.
- Develop improved casting processes.
- Identify and/or develop methods to improve corrosion resistance.
- Improve joining technologies.
- Transfer knowledge and lessons learned to industry.
- Complete all scientific project tasks relevant to microstructure-property modeling, corrosion mitigation, joining behavior and nondestructive evaluation (NDE) methods, etc.
- Redesign an existing aluminum (AL) cradle to Mg and produce validation-ready components for testing and approval for Corvette's 2006, Job #1 requirements as shown (see Figure 1).

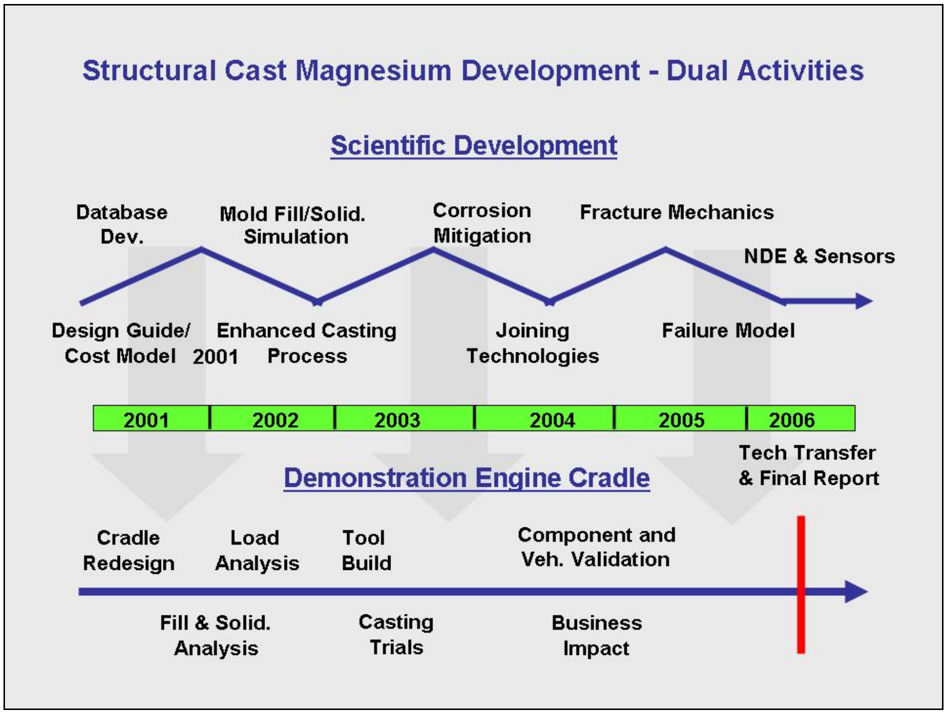

Figure 1. Dual-project path for science and Mg demonstration casting validation activities.

Accomplishments

- Completed Mg-to-Al cradle re-design and finite-element analysis (FEA).
- Produced 150 prototype components and conducted sub-system and full-vehicle validation with no issues reported.
- The Mg cradle achieved a 5.5 kg reduction in weight (35%) with respect to the current Al cradle now used in production applications (See Figure 2).
- Completed mechanical-property and microstructural characterization of numerous Mg-alloy production components.
- A new high-temperature creep-resistant alloy AE44 was developed by participating team member Hydro Magnesium, which successfully completed bench and vehicle testing.
- CANMET's corrosion studies showed the need for dissimilar-metal isolation requirements.
- CANMET's bolt-load retention (BLR) analysis demonstrated that the cradle attachments would meet vehicle performance requirements.
- SCMD team developed and implemented a successful galvanic-corrosion mitigation strategy which proved successful in bench and vehicle validation testing. SCMD database material testing was completed and provides computer-aided engineering (CAE) properties.
- Mississippi State University (MissU) and Sandia National Laboratory (SNL) completed material-testing quantitative microstructure characterization and successfully exercised their multiscale static and fatigue models.
- Lawrence Livermore National Laboratory (LLNL) completed fabrication of several ASTM E5505 Radiographic Inspection Standards (RIS) which will improve casting evaluation sensitivity.
- The project demonstration cradle passed all validation requirements with no issues and is now in volume production on the 2006 Z06 Corvette.

- SCMD and MCPP (see report 2.H) project teams developed and published a Magnesium 2020 document which outlines a North American strategic vision (from 2005 through the year 2020) for automotive weight reduction using Mg components.
- The SCMD database has been improved with a new navigation system and additional property inputs.
- The list of SCMD publications and presentations are included in the final report published 8/29/06.

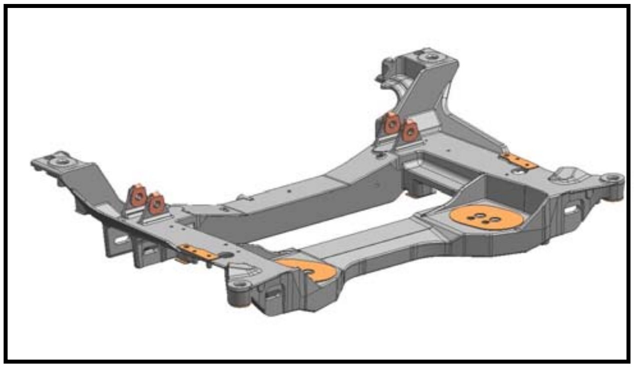

Figure 2. Machined Mg cradle.

Future Direction

- The SCMD project made significant scientific and application progress, but this project alone is insufficient for Mg to realize its full vehicle weight-saving potential without a dedicated long-term vision to focus future research and development efforts. Therefore, the scope of the SCMD project was increased on 3/9/05 to develop an industry vision that outlined the potential to increase the use of magnesium (North American Automotive) from 12 pounds (5.5 kg.) / typical vehicle in 2005 to 250 pound (114.6kg.) /typical vehicle in 2020. The document *Magnesium Vision 2020* was completed and included with the SCMD project report published on 8/29/06. Copies of the *Magnesium Vision 2020* document are available through the USCAR Office.
- The SCMD Core Team completed the preliminary investigation of the low-pressure permanent-mold (LPPM) casting process to cast a duplicate Mg cradle by this alternative casting process. Future work will continue with the High-Integrity Mg Automotive Casting (HI-MAC) project (see 2.J).

Introduction

The SCMD project focused on resolving critical issues that limited the large-scale application of Mg castings in automotive components. The project activities combined the science and manufacturing technology necessary to implement front and rear structural cradles. Such components offer all of the difficult manufacturing issues, including casting process (high-pressure die, semi-solid, low-pressure, squeeze, etc) and joining, along with harsh service environment challenges, such as corrosion, fatigue, and stress relaxation associated with fasteners.
The project team included personnel from:

- The “Big Three” automotive companies
- 34 companies from the casting supply base
- Academic personnel
- Independent testing and research labs
- American Foundry Society (AFS)
- Technical Associations
- Oak Ridge National Laboratory (ORNL)
- Sandia National Laboratory (SNL)
- Lawrence Livermore National Laboratory (LLNL)
- Natural Resources Canada (CANMET)

Industry Participants

An existing Al engine cradle (that is currently in production use) was redesigned for two different Mg casting processes: high-pressure die casting (HPDC) and low-pressure permanent-mold (LPPM). Utilization of computer simulations (prior to tooling design) indicated good correlation of casting fill operation (and their effects) to actual production experiences (see Figure 3).

Tooling and castings were made for both processes. Several hundred HPDC production prototype castings were distributed to SCMD project participants and to the GM Corvette Team for the rigorous testing procedures that were required for the HPDC cradle (see Figure 4). Based on the results of the ongoing tests, the Corvette Team decided to start a parallel production program for the implementation of using a Mg cradle for the 2006 Z06 Corvette.

The LPPM process (see Figure 4-A) will continue further development with the HI-MAC project approved on 4/1/06 (see 2.J).

Importance/Significance: Utilization of up-front computer modeling (used for both HPDC and LPPM processes) resulted in significant savings (time and costs) and eliminated casting defects in the initial castings. Based on the prototype castings produced

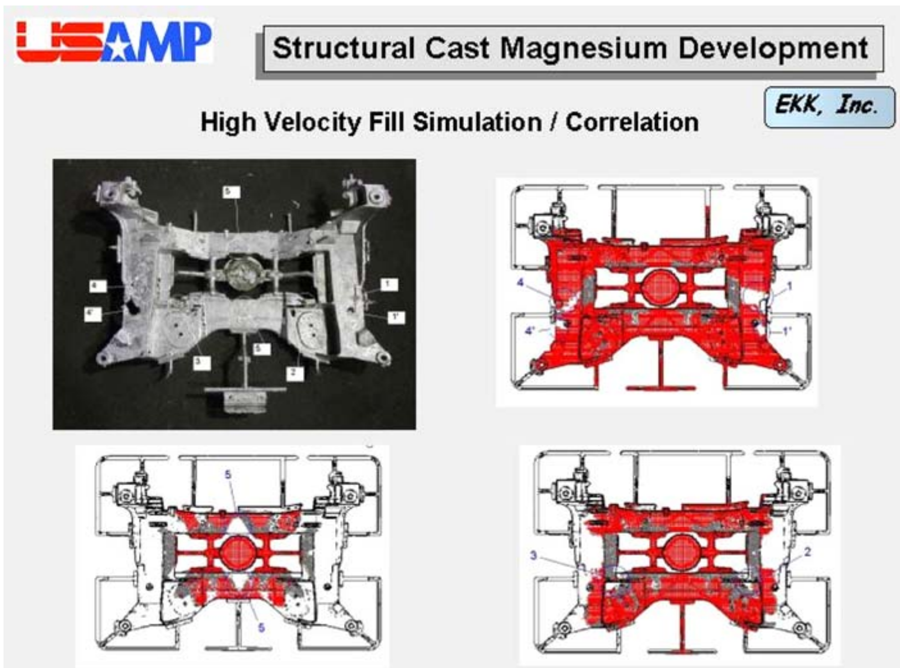

Figure 3. EKK, Inc. cavity-fill simulations show excellent correlation with short-fill HPDC castings.

Figure 4. Initial machined HPDC cradle castings.

Figure 4-A Initial LPPM Mg cradle.

by both processes, there was an estimated 35% weight savings in the Mg cradle versus the current Al production part. The investigation of producing the same casting by the two different processes (HPDC and LPPM) has a great potential for the utilization of existing Al casting companies to expand their operations into Mg without huge capital and facility expenditures.

Project progress/status vs. targets

The project targets for 2006 were to complete the outstanding Statements of Work for the final project report to meet Job #1 2006 objective for Corvette (completed), and to complete the Magnesium 2020 document (completed).

Remaining Technical Challenges and Plans

The SCMD project completed the outstanding Statements of Work, and the Final Report was published and distributed to all project participants on August 29, 2006.

<u>Milestones</u>

Cooperative Agreement

Mg front cradles (HPDC process) passed all bench and vehicle testing; actual testing results coincided with predicted computer-modeling techniques. All tasks were completed on time to meet Corvette's evaluation of installing a similar Mg cradle for Job #1-2006 production vehicle.

A new high-temperature, creep-resistant alloy AE44 was developed by a participating project team member who successfully completed bench and vehicle testing.

Detailed quantitative microstructural characterizations were completed for other production components cast with AZ91D, AM 50 and AM 60 Mg alloys. CANMET's corrosion studies showed (see Figure 6) the need for dissimilar metal isolation. CANMET's BLR analysis demonstrated that the Mg cradle attachments would meet vehicle performance requirements.

Cooperative Research and Development Agreement (CRADA)

ORNL—ORNL completed the investigation of modeling software from four of the supply teams. The results of the investigation were applied to the ORNL models using current commercial software; ORNL completed the investigation of the effects of using die lube for HPDC and LPPM operations (see Figure 5).

Importance/Significance: These investigations (real time and software proven) indicated that gas can be generated from the lube when molten metal (higher temperature) is introduced into the mold cavity. The gas then disperses throughout the casting, causing various types of porosity defects.

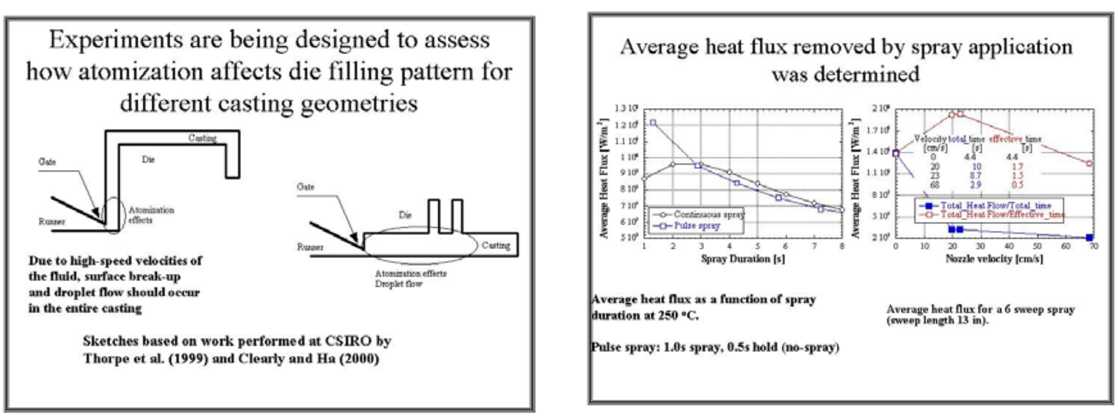

Figure 5. ORNL die-lube investigation work.

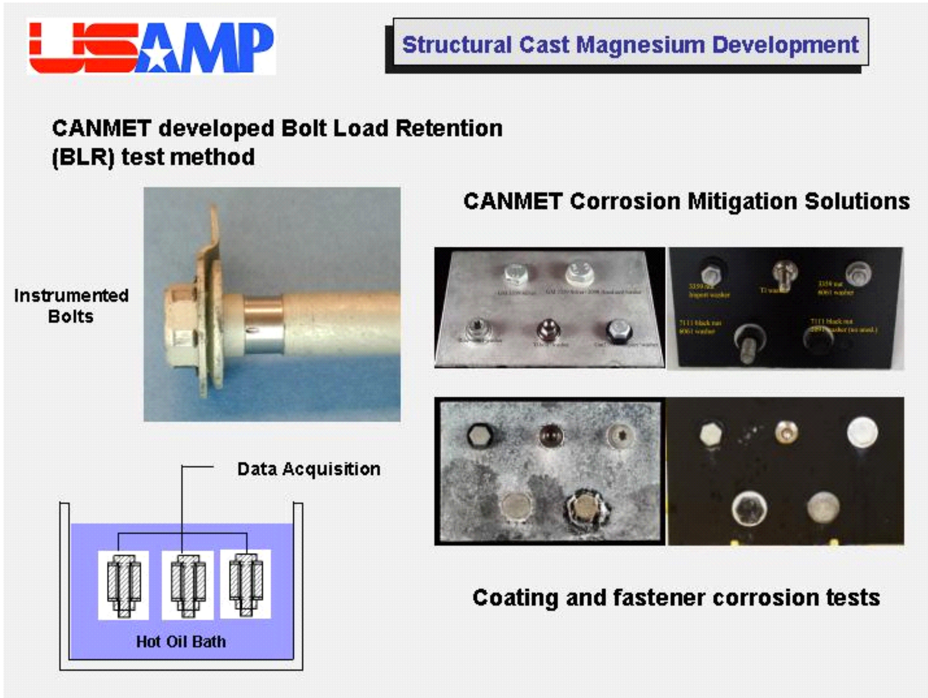

Figure 6. CANMET bolt-load retention testing and corrosion studies developed knowledge required for product implementation.

SNL/MisSU—SNL coordinated the collection of project data from all the SCMD project testing sites and then used the data to expand the mathematical "failure model" (see Figure 7).

Importance/Significance: Designers can use the multiscale fatigue model to develop castings with the accurate knowledge of providing known failure points**.**

LLNL— LLNL completed the fabrication of several ASTM E505 Reference Quality Indicators that will improve casting evaluation sensitivity (see Figure 8); performed radiographic analysis of production parts and test samples to determine discontinuity types and grades at predicted high-stress locations; investigated the possibility of using fiber-optic, in-mold thermal monitoring for HPDC

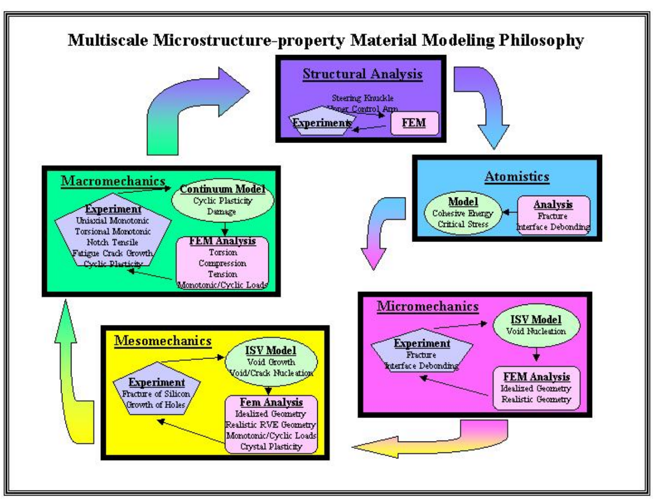

Figure 7. SNL damage model for simulating component material properties.

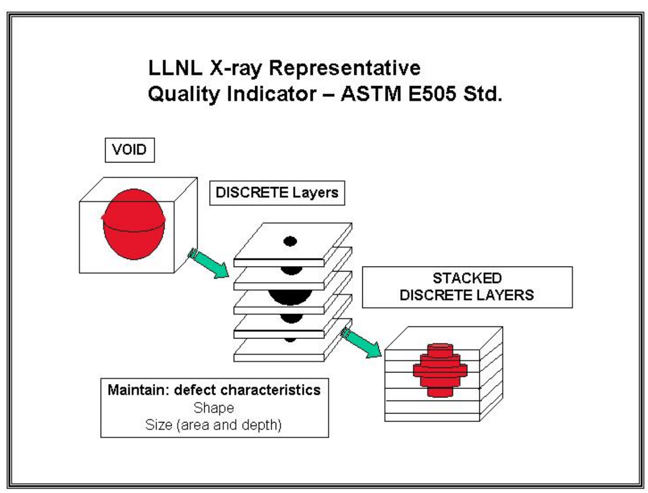

Figure 8. LLNL development activities.

in a high-volume production facility; worked with suppliers to provide a system to detect impurities in the metal that is charged into the furnace.

Importance/Significance: All of the above procedures and investigations will provide more consistent and measurable standards that are required for improved quality control and to improve the safety critical components that are cast in Mg

Academia participants: Academia participation in the SCMD project was involved with: the investigation of and characterization of crack nucleation and growth; the investigation into the cause of casting defects and the ability to separate gas and shrinkage effects that are generated (in the casting) by the various processes. (See Figure 9)

Importance/Significance: The importance of understanding the crack nucleation and the results of gas generated in Mg castings will help to provide tools to manufacturing (or change process parameters) to eliminate casting defects. Both of these investigations by academia worked with the information supplied by ORNL and sample parts provided by the manufacturing team. The understanding of the gas effects in castings, generated by die lube is a major breakthrough in understanding defects in Mg castings.

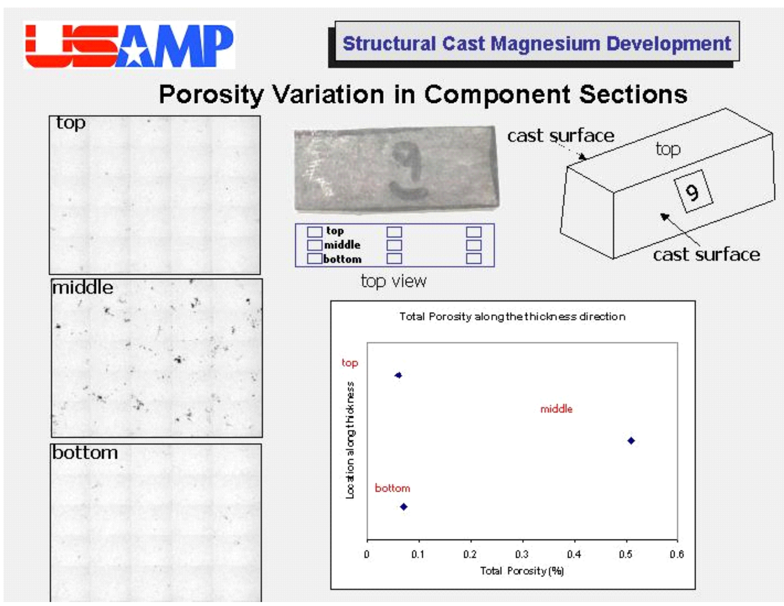

Figure 9. Georgia Institute of Technology characterization of AE44 alloy HPDC cradle section.

Project Benefit

The DOE and U.S. industry benefits derived from the successful completion of this CRADA includes vehicle mass savings for ground and air transportation, leading to reduction in fuel consumption, emissions, and less dependence on foreign oil.

The North American (NA) auto industry currently uses approximately 12 pounds (5.5 kg) of Mg per vehicle per year. The ability to significantly increase Mg usage will help the auto industry meet future Federal Corporate Average Fuel Economy (CAFE) targets and reduce exposure to CAFE penalties. Cast Mg structures have the potential to reduce 100 kg of vehicle mass, which could reduce emissions by 5% and reduce fuel consumption by approximately 1.0 mpg (ignoring secondary mass savings).

Light-metal alloys have greater recycling value with reduced energy consumption versus plastics (including melting, machining, handling, and transportation energy requirements).
The Big Three competitive global postures will increase as a result of designing and manufacturing

vehicles that offer greater consumer value. This can improve the U.S. trade balance with countries that market higher fuel efficiency vehicles than those produced in North America.

Health and environmental issues for workers are reduced during light-metal casting operations when compared to ferrous foundries and polymer-molding operations.

Participation provides the national laboratories with valuable manufacturing-development and product-application experience.

The dual purpose role of providing the national laboratories (and academia) an opportunity to develop math-based simulation models and NDE technologies, benefits both the auto industry and federal ongoing technology programs.

The preliminary studies completed by the casting of a M cradle (by low-pressure die casting) has indicated to the existing Al casting industry that the transfer of casting technology (Al to Mg casting) can be achieved at a low facility cost, and additional work will continues with the HI-MAC Project.

Conclusion

The SCMD project has proven the successful casting (and recent production use) of a Mg engine cradle is a major accomplishment for NA Mg casting industry. Most important, the project success has proven that the technical and manufacturing issues (high-integrity castings, corrosion & joining) that have heretofore limited the light weighting application of structural cast Mg automotive cradles, was successfully solved in the SCMD project.

OEM's Presentations and Publications

Approximately 315 presentations were made by SCMD Project Team Members and Principal Investigators at Quarterly Review Meetings (QRM) and OEM presentations. The QRMs held are listed below.

Year	Meeting	Date	Location
2000	QRM #1	05/15/2000	USCAR Office Building
	(General Presentation to Proposed Project Participants)		
2001	QRM #1	03/20/2001	Meridian Technologies
	QRM #2	Cancelled	
	QRM #3	09/26/2001	WMTR
	QRM #4	12/11/2001	USCAR Office Building
2002	QRM #1	03/29/2002	SNL
	QRM #2	07/30/2002	Alfred University
	QRM #3	09/23/2002	WMTR
	QRM #4	12/11/2002	Hayes-Lemmerz
2003	QRM #1	02/11/2003	USCAR Office Building
	QRM #2	05/14/2003	Gibbs Die-Casting Plant
	QRM #3	07/25/2003	WMTR
	QRM #4	12/09/2003	USCAR Office Building
2004	QRM #1	03/03/2004	Hayes-Lemmerz
	QRM #2	05/26/2004	USCAR Office Building
	QRM #3	09/21/2004	USCAR Office Building
	QRM #4	12/08/2004	USCAR Office Building
2005	QRM #1	04/07/2005	USCAR Office Building
	QRM #2	06/28/2005	WMTR
	QRM #3	09/14/2005	WMTR
	QRM #4	12/07/2005	USCAR Office Building
2006	QRM #1	Cancelled	
	QRM #2	08/29/06	USCAR Office Building Final Meeting

Miscellaneous Presentations:
12/7/04 Chinese Magnesium Conference and Global Collaboration at USCAR Office
10/11/05 Preliminary Review of Magnesium 2020 Document at USCAR Office

SAE World Congress Presentations
2001 through 2006: Numerous presentations by SCMD Project Chairman and OEM Representatives all properly noted in SAE Proceedings.

Representative Sample of Publications / Presentations by OEMs & PIs

Presentations

S.G. Lee, A.M. Gokhale, and G.R. Patel, "Macro-Segregation in High-Pressure Die-Cast AM60B Alloy," Magnesium Technology 2005 Symposium, TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

S.G. Lee, G.R. Patel, A.M. Gokhale, and Mike Evans, "Effects of Liquid Metal Gate Velocity on the Porosity in High-Pressure Die-Cast AM50 Alloy," *Magnesium Technology 2005 Symposium,* TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

A. Sreeranganathan, Soon Gi Lee, and A. M. Gokhale: "Quantitative Characterization of AM50 and AS21X Magnesium Alloys to Correlate the Variability in the Fracture Properties to Microstructure," *Automotive Alloys 2005 Symposium,* TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

Soon Gi Lee, Arun Sreeranganathan, and A.M. Gokhale: "Simulation of Mechanical Behavior of Die-Cast Magnesium Alloy Based on Three-Dimensional Porosity and Finite Elements Method," *Symposium on Computational Aspects of Mechanical Properties of Materials: Meso-Scale and Continuum Modeling,* TMS Annual Meeting, San Francisco, CA, February 14-17, 2005.

Soon Gi Lee and A.M. Gokhale: "On the Formation of Gas (Air) Induced Shrinkage Porosity in Pressure Die-Cast AM60 Mg-Alloy," Symposium on Defect Formation, Detection, and Elimination During Casting, Welding, and Solidification: Processing, Microstructure, and Properties, *Materials Science and Technology 2005* (MS&T 2005), Pittsburgh, PA, September 26, 2005.

Soon Gi Lee, G.R. Patel, and A.M. Gokhale: "Variability in Tensile Ductility of High-Pressure Die-Cast AE44 Mg-Alloy," Symposium on Defect Formation, Detection, and Elimination During Casting, Welding, and Solidification: Processing, Microstructure, and Properties, *Materials Science and Technology 2005* (MS&T 2005), Pittsburgh, PA, September 26, 2005.

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[i] Denotes project 111 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.