# 3. AUTOMOTIVE METALS – CAST

## A. Improved Automotive Suspension Components Cast with B206 Alloy (AMD 405[i])

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*Contractor: United States Automotive Materials Partnership (USAMP)[i]*
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### Objective

- The objective of this project is to establish the commercial viability of B206 alloy for suspension components, by providing needed fundamental information on this alloy system and by overcoming technical issues that limit the lightweighting applications of this alloy. The B206 alloy has the potential to provide near net-shaped castings with mechanical properties equivalent to forged aluminum (Al) suspension components and ferritic ductile iron.

### Approach

Four major technical focus points have been identified for this project. Accordingly, the work will be conducted in four separate phases:

1. Determine the effect of alloy composition on mechanical properties in the T4 and T7 heat-treated conditions and establish the feasibility of using less expensive versions of the alloy.
2. Study heat treatment of B206 alloy and establish combinations of aging time and temperatures which produce desirable stress-corrosion immunity. This portion of work will also determine the feasibility of using improved T7 heat-treatment cycles to increase elongation in this temper.
3. Create cost models for automotive suspension components produced by different processes and different materials.
4. Produce control-arm castings using two different casting processes. Test components produced in the T4 and T7 tempers to provide required engineering information and establish the feasibility of using cast B206-alloy components to replaced forged Al parts.

### Accomplishments

- The project was officially kicked off in October 2005.
- Dr. Geoffrey Sigworth, the initial Project Technical Consultant (PTC), resigned from the program. Dr. Murat Tiryakioğlu took over the PTC responsibilities in March 2006.
- Phases 1, 2 and 3 have been completed.

- Phase 4 is ongoing. As of December 2007, 30 B206-T4 and T7 suspension control-arm castings were produced at Nemak and delivered to Chrysler. The project was extended until April 2008 to produce castings and complete Phase 4. Ballard Brass & Al, Inc. was selected to produce semi-permanent-mold castings, an economically favorable process that is typically used for the B206 alloy. Eck Industries/Alotech was selected to produce castings using the ablation process; a direct-chill process that is well suited to the B206 which responds better to fast cooling rates. Both suppliers are scheduled to start production of the castings in early January 2008, with mechanical testing planned for February 2008.

**PHASE 1:**

**Phase 1** is complete and consisted of two separate studies. The first study was to identify the optimum chemistries for the T4 and T7 tempers and the second study was to evaluate the effect of cooling rate on the properties of B206 in the T4 and T7 tempers.

**Phase 1, Part 1:**

A study of tensile properties versus alloy composition was conducted by researchers at Alcan International. These results show that best results for the T4 and T7 tempers are obtained with two separate alloy compositions. The two alloy compositions and expected properties are provided below (in wt.%):

1. T4 Temper

The alloy contains 4.7 to 4.9% copper (Cu), 0.35 % magnesium (Mg) and 0.2 % manganese (Mn). The expected tensile properties are yield strength (YS) 250-260 MPa, ultimate tensile strength (UTS) 430-450 MPa, and elongation 18-22%.

2. T7 Temper

For a ductile T7 version, the alloy contains 4.2 to 4.4% Cu, 0.15% Mg, 0.2% Mn, 0.10% iron (Fe), 0.10% silicon (Si). The expected average tensile properties would be YS: 370-390 MPa, UTS: 445-455 MPa, and ~9% elongation.

In addition to the above results, a set of casting guidelines has been prepared for foundrymen who want to pour B206 alloy.

**Phase 1, Part 2**

A second stage of Phase 1 casting trials was completed in September 2005 by Nemak researchers at their Central Development and Technology Center near Monterrey, Mexico. Several different alloy compositions were prepared and ‘wedge’ castings were made. The ‘wedge’ castings were poured to establish the tensile properties of the alloy as the solidification rate varied from 30 seconds to 30 minutes. In addition, hot-crack-test castings were poured to determine the effect of alloy composition on castability.

**PHASE 2:**

**Phase 2** was conducted at the University of Windsor under the direction of Prof. Jerry Sokolowski. Alcan International also assisted this phase of the project by providing additional testing. A survey study of the aging of B206 alloy was completed. Samples were aged at temperatures between 125$^{o}$C and 225$^{o}$C for times ranging from two to forty-eight hours. The hardness and electrical conductivity were measured and the samples were subjected to a corrosive medium to establish their vulnerability to intergranular attack. A report of these experiments was issued in October 2005. Additional studies were conducted to establish the kinetics of the solution heat-treatment process. Attempts to develop an alternative T7 aging process to increase elongation in that temper were mostly unsuccessful.

**PHASE 3:**
**<u>Phase 3</u>** has been completed. A cost model was developed by Edmund A. Herman, P.E., of Creative Concepts Company, Inc. in March 2006. A Microsoft Excel spreadsheet was developed which can be used to compare costs of producing castings using A356-T6, B206-T4 and B206-T7 alloys.

**PHASE 4:**
**<u>Phase 4</u>** is in progress. The intent of Phase 4 was to produce and test B206 castings using green sand at Hayes Lemmerz and precision sand at Nemak. Mercury Castings was added in September 2005 to produce castings using their Slurry-on-Demand process.

Hayes Lemmerz
The design work for the castings was completed in April 2006. Dr. Tiryakioğlu and Prof. John Campbell provided the optimum gating and filling system to minimize the entrainment of surface oxide films and therefore maximize mechanical properties. However, Hayes Lemmerz closed their Ferndale, Michigan facility and discontinued their involvement in the program before castings could be made.

Mercury Castings
Mercury Marine attempted to make castings but was unable to produce acceptable quality castings. No further work with Mercury Marine is planned.

Nemak
The gating system design concepts proposed by Tiryakioğlu and Campbell were adopted by Nemak and final gating system design, as shown in Figure 1, was developed with the assistance of Prof. Campbell. Mold-filling simulations using Magma software showed significant improvement over previous designs.

**Figure 1.** The gating and feeding system design used by Nemak.

Initial trial castings poured at Nemak with complete sand cope and drag showed extensive porosity and metal-mold reaction problems. Consequently, the mechanical properties, especially elongation, and surface finish of castings did not meet expectations (YS=270 MPa, UTS=310 MPa, elongation=10%). Based on Phase 1 results, the Project Team concluded that the solidification rate in the full sand mold was the primary reason why the castings did not achieve the desired properties.

To increase the cooling rate, Nemak machined an Al drag, poured thirty castings and heat-treated the castings in the T4 and T7 tempers. The results were encouraging but neither temper fully achieved the targeted mechanical properties. The T4 temper missed the target yield stress by 5%. The T7 temper greatly exceeded the UTS and YS targets but failed to achieve the targeted 10% elongation. Unfortunately, due to business conditions, Nemak had to withdraw from the program. Nemak delivered the metal drag and sand cope to Chrysler in the event that another supplier may be able to cast the parts.
Ballard Brass & Al, Inc.

Ballard will produce 50 castings using the semi-permanent-mold process. First four castings are scheduled to be produced in December 2007 and subsequently heat-treated to T7 condition. The team will decide whether any changes on the tooling are necessary, based on the tensile properties of the first four castings. Once the process has been optimized to produce castings with pre-targeted properties, 25 castings will be produced using the T7 chemistry and heat-treated to the T7 condition followed by 25 castings with the T4 chemistry heat-treated to the T4 temper.

Eck Industries/Alotech
Eck Industries and Alotech will produce 50 castings, 25 of the T4 temper and 25 of the T7 temper, with the ablation process, which generates high cooling rates and low levels of porosity. Castings are scheduled to be poured in early January 2008 using the same T4 and T7 chemistries and heat-treat schedules as the semi-permanent-mold castings.

**Component Testing**
General Motors and Westmoreland Mechanical Testing and Research are currently awaiting castings to be tested in component fatigue, tensile, fracture toughness, compressive testing and corrosion. This testing has been postponed since suppliers have been unable to produce castings to the desired quality and mechanical properties.

In addition to component testing, deformation characteristics will be evaluated to determine whether any outliers in tensile tests are due to structural defects that can be avoided with better melt quality and modifications to mold-filling system design. A full project report will be available in May 2008.

## Future Direction

- The Project Team believes that it is possible to achieve the targeted properties and is currently investigating a lean chemistry to boost the T4 yield and direct cooling (ablation) or heat-treat optimization to improve the T7 elongation. The two casting processes selected for the production of the control-arm castings, namely, ablation and semi-permanent-mold, are expected to meet the target mechanical properties. The project will be finalized in May 2008.

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## Introduction

B206 alloy is significantly stronger than 356 alloy, and has mechanical properties approaching some grades of ductile iron. It also has excellent high-temperature tensile and low-cycle-fatigue strength. Consequently, this material could be used in a number of applications to reduce vehicle weight. Cost savings may also result, because less material would be required to provide the strength needed for the application. In spite of its excellent properties, 206 alloy is seldom used because of its propensity for hot cracking. GKS Engineering has discovered a better method to grain refine this alloy, which reduces the tendency for hot cracking. This material has a number of potential applications, but its high strength and excellent ductility make it an ideal candidate for suspension components. Consequently, in the first stage of work (Project AMD 305 -- completed in May 2002) control arms were produced via a tilt-pour/permanent-mold casting process to establish the viability of this material for these safety-critical components.

The work completed under AMD 305 showed that extremely high mechanical properties can be obtained. The tensile properties of permanent-mold B206-alloy control arms were nearly the same as (or slightly better than) those found with many forged Al components, and the low-cycle-fatigue life of B206 alloy is ten times that of A356 alloy castings for an equivalent stress level. AMD 305 also showed that the permanent-mold-casting process, although suitable, may not be the best manufacturing process for 206 alloy. Traditional sand-casting and composite-casting methods (such as Nemak´s semi-permanent-mold, precision-sand-casting process) are more forgiving of hot cracking. The additional work in this present project examines the technical feasibility of producing B206 alloy suspension components in three other casting processes. Other important technical and commercial issues related to B206 will also are addressed. The object is to provide the technical and economic data needed to justify commercial use of this material in suspension components.

## Justification

Automakers are under increased pressure to reduce carbon dioxide ($CO_2$) emissions and improve fuel economy through increased Corporate Average Fuel Economy (CAFÉ) standards. Because of its higher strength, B206 alloy structures have the potential to reduce vehicle mass, which is directly linked to improved CAFE and vehicle performance. There is also a potential for cost savings, because less material would be required when compared to conventional Al castings.

## Program and Deliverables

This project was initially planned to be completed in 30 months and preceded in four stages. Below is a description of the deliverables for each of the four phases of the project.

Phase 1

The main alloying elements in 206 alloy (Cu, Mg, Mn) will be varied in a series of statistically-designed experiments. Test bars will be cast at each composition and heat-treated to the T4 and T7 tempers. Hot-crack-test castings will be made to study the effect of alloy composition on castability, and 'wedge' castings will also be poured to determine the effect of solidification rate on tensile properties. These tests will determine the effect of alloy composition on mechanical properties and castability, and will allow design and casting engineers to better tailor mechanical properties for any specific application. The minor impurity elements (Fe and Si) will also be varied to determine the effect of these elements on mechanical properties. It appears that the maximum limits for Fe and Si, presently listed in the Aluminum Association (AA) specifications for the 206 alloys, are lower than necessary for most automotive applications. Increasing these limits by a modest amount would reduce the cost of the alloy. These tests will be conducted at the Research and Development Center of Alcan International and at Nemak.

Phase 2

Parts made in 206 alloy are immune to stress corrosion in the T4 and T7 tempers. Parts that have been aged to peak strength (T6), however, are susceptible. Published information on other Al-Cu-Mg alloys suggests that relatively short aging times may induce stress corrosion, and that the susceptibility to stress-corrosion may occur before any change in hardness is found. For example, the temperatures and times used in powder coating may cause a problem. This part of the study will map out the dangerous areas which must be avoided. It will also examine alternative T7 treatments, to see if there is a way to improve material properties (especially elongation) in this temper. The use of alternative methods to test for stress corrosion resistance will also be evaluated. The standard test is cumbersome and takes 30 days to complete. A simpler, more rapid test is desirable. This phase of work will be carried out at the University of Windsor in Windsor, Ontario, and at Westmoreland Mechanical Testing Laboratories. Additional support will be provided by the laboratories of Alcan International.

Phase 3

A cost model will be constructed for suspension components manufactured using different processes and materials. A General Motors front-left control arm (FLCA) forged in 6xxx alloy will serve as a mule for this economic study. The following component cases will be considered:

- -forged 6xxx alloy
- -sand-cast B206 alloy
- -semi-permanent-mold-cast B206 alloy
- -permanent-mold-cast A356 alloy

Creative Concepts will assist the project group in formulation of the cost models in this portion of the study. Sync Optima will also do finite-element modeling (FEM) studies of the different cases, to determine changes required in the design (and weight) of the control arm as the material is changed from the base condition (forged 6xxx alloy).

Phase 4

In this final stage of work, a control arm 'mule' casting will be manufactured by the composite precision-sand-casting process at Nemak. Semi-solid cast parts will also be made at Mercury Castings.

In AMD 305, parts were made and heat-treated to the T4 temper. In this new work, additional castings will be made and tested in both the T4 and T7 tempers. In this way, a complete set of mechanical-property data will be obtained for the castings.

For this portion of the project, the compositions used to produce castings will be the optimum alloy compositions mapped out in Phase 1 of the project.

Westmoreland Mechanical Testing and Research will do testing of castings made in this phase of work.

## Measurable Success Indicators

The successful results desired from each of the four phases of work are outlined below:

**Phase 1**
Mechanical properties as a function of cast material composition will be provided, allowing automotive design engineers to optimize component properties at lowest possible cost. Information will be provided that may allow us to increase upper limits for dissolved Si and Fe and reduce costs in 206 alloy.

**Phase 2**
Optimum heat-treatment schedules, which avoid stress-corrosion problems, will be established and recommended. Simple and rapid tests for stress-corrosion susceptibility will also be evaluated.

**Phase 3**
Cost models will be provided for the production of suspension components using several manufacturing processes and different materials. This model will assist automotive design engineers to optimize component performance and, at the same time, to help realize production cost savings.

**Phase 4**
Control-arm castings will be produced using two different casting processes and a complete battery of material property tests of the components will provide the technical database needed to design, manufacture and use suspension components cast in B206 alloy.

## Technical Results

The results of the Phase-1 casting trials have been used to map out the range of mechanical properties that can be obtained from B206 alloy castings. For permanent-mold test bars, which have a relatively rapid solidification rate (20-30 seconds), the tensile properties found in the T4 temper are shown in Figure 2. The irregular polygon in these figures indicates the variation of tensile properties (UTS or YS and elongation) that one may expect as the composition is varied between the upper and lower limits for this alloy in the AA specifications. The amounts of Cu, Mg, Mn, Fe and Si in the alloy were all allowed to vary. The corresponding range of mechanical properties available in the T7 temper is indicated below in Figure 3.

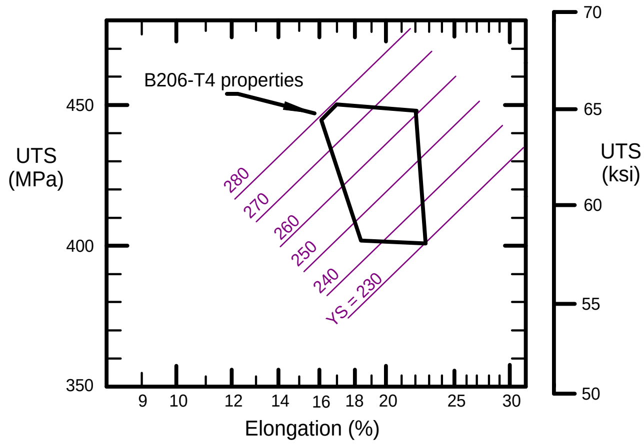


**Figure 2**. B206-T4 tensile properties.

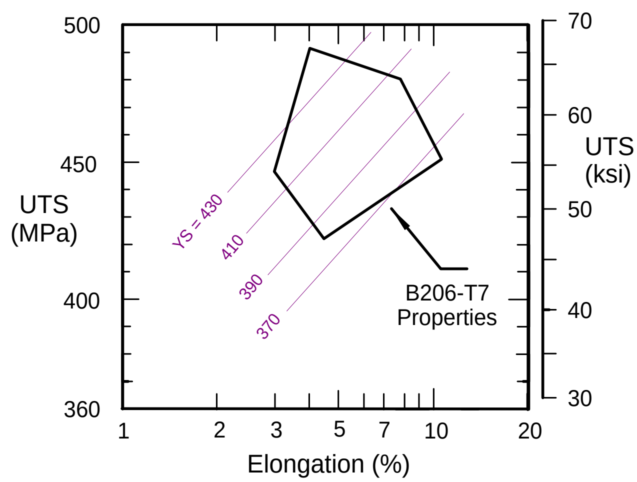


**Figure 3.** B206-T7 tensile properties.

In addition to the above results, two of the Alcan alloy compositions were poured into an end-chill mold. Tensile samples were cut at three distances from the chill (ranging from 12.5 to 50 mm (½ to 2 inches)). The tensile properties obtained from these castings are shown Figure 4, together with data published for the more commonly used Al casting alloys.

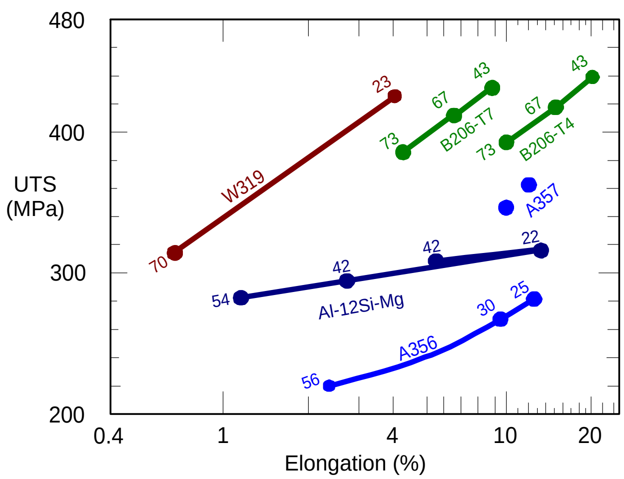


**Figure 4.** Range of mechanical properties in five Al casting alloys.

The solidification time is indicated in this figure by numerical values for the secondary dendrite-arm spacing (SDAS), or the cell size in the case of B206 alloy. (The data for A357 alloys is for heavily-chilled sections of aerospace castings only.) It can be seen that B206 alloy exhibits mechanical properties superior to the conventional Al-Si-Mg and Al-Si-Cu casting alloys.

A number of B206 alloy samples were aged and tested for intergranular attack by corrosion. A test procedure outlined in Mil Spec MIL-H-6088 and American Society for Testing and Materials (ASTM) specification G110 was used. This procedure correlated well with the results of a standard alternate immersion test in 201 alloy, [1] and so it was adapted for use in Phase 2 of this study. The average depth of the intergranular attack by corrosion (in microns) is plotted in Figure 5, as a function of aging time and aging temperature. In Figure 5, the safe aging conditions are indicated by the hatched areas. (These areas indicate aged samples where the average intergranular-corrosion depth was less than 20 µm deep.) The areas of worst corrosion attack are between the safe areas, at aging temperatures between 100°C and 180°C.

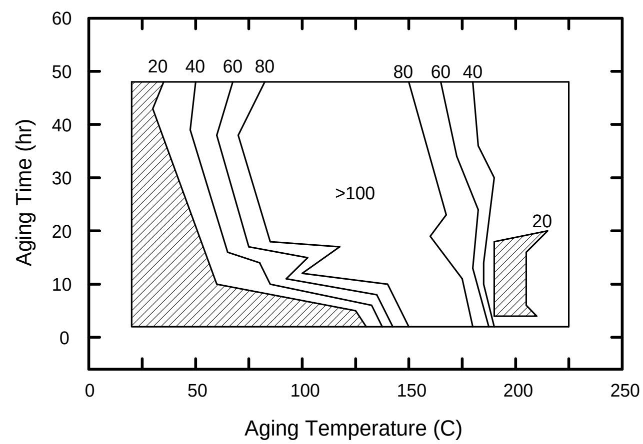


**Figure 5.** Average depth of corrosion.

In Phase 2 of our program, immersion stress-corrosion tests were conducted in accordance with the ASTM G47-98 standard. Specimens were all naturally aged for 3 days and artificially aged for different durations at temperatures between 100°C and 225°C. The stress-corrosion cracking (SCC) life contour plot is provided in Figure 6 as a function of artificial aging temperature (T) and time. The worst stress-corrosion life occurred between 100°C and 175°C, which is consistent with intergranular-corrosion results outlined in Figure 6. More analysis will be conducted for possible correlation between the results from the two test methods.

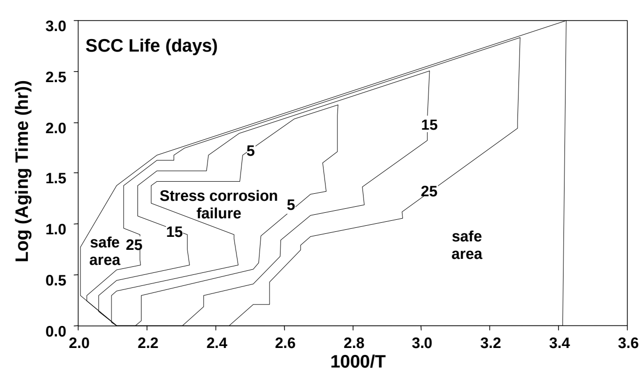


**Figure 6.** Stress-corrosion cracking life contours as a function of artificial aging time and temperature.

Contour plots of tensile properties after artificial aging at temperatures between 100°C and 225°C for various durations are presented in Figure 7. Highest UTS and elongation are obtained at an artificial

[1] M.S. Misra and K.J. Oswalt: "Corrosion Behavior of Al-Cu-Ag (201) Alloy," Metals Engineering Quarterly, Vol. 16, pp. 39-44 (1976).

aging for 12-24 hours at 125$^o$C. A small set of experiments is planned at Alcan Laboratories to obtain more detailed results.

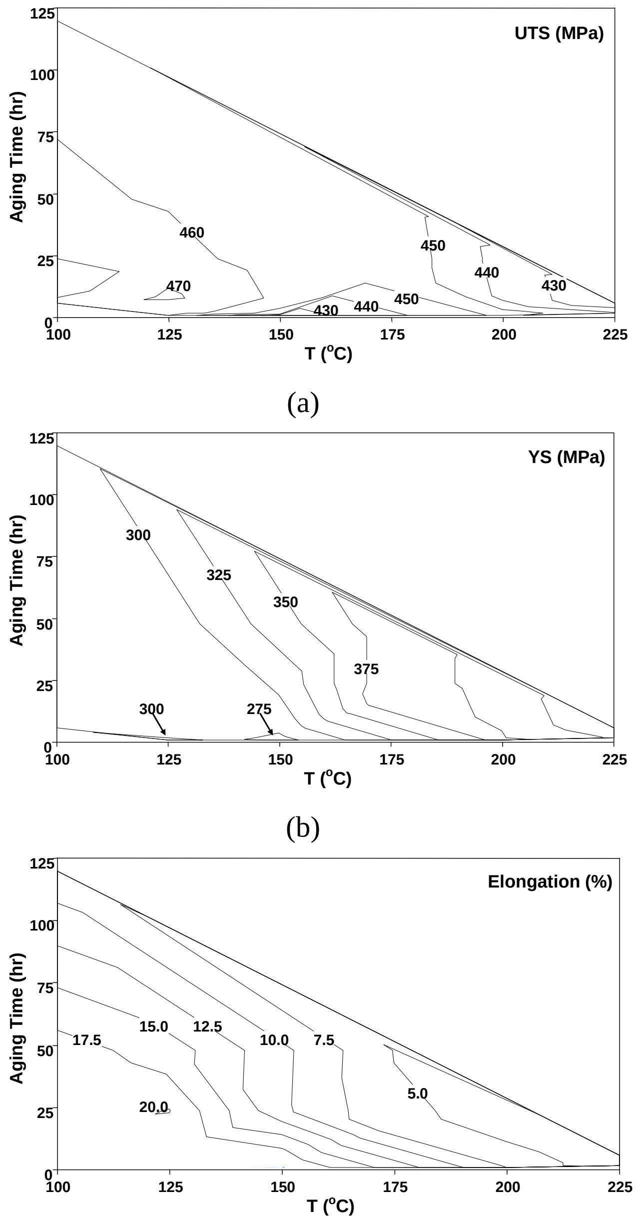


**Figure 7**. Contour plots for (a) ultimate tensile strength, (b) yield strength and (c) elongation as a function of artificial aging time and temperature.

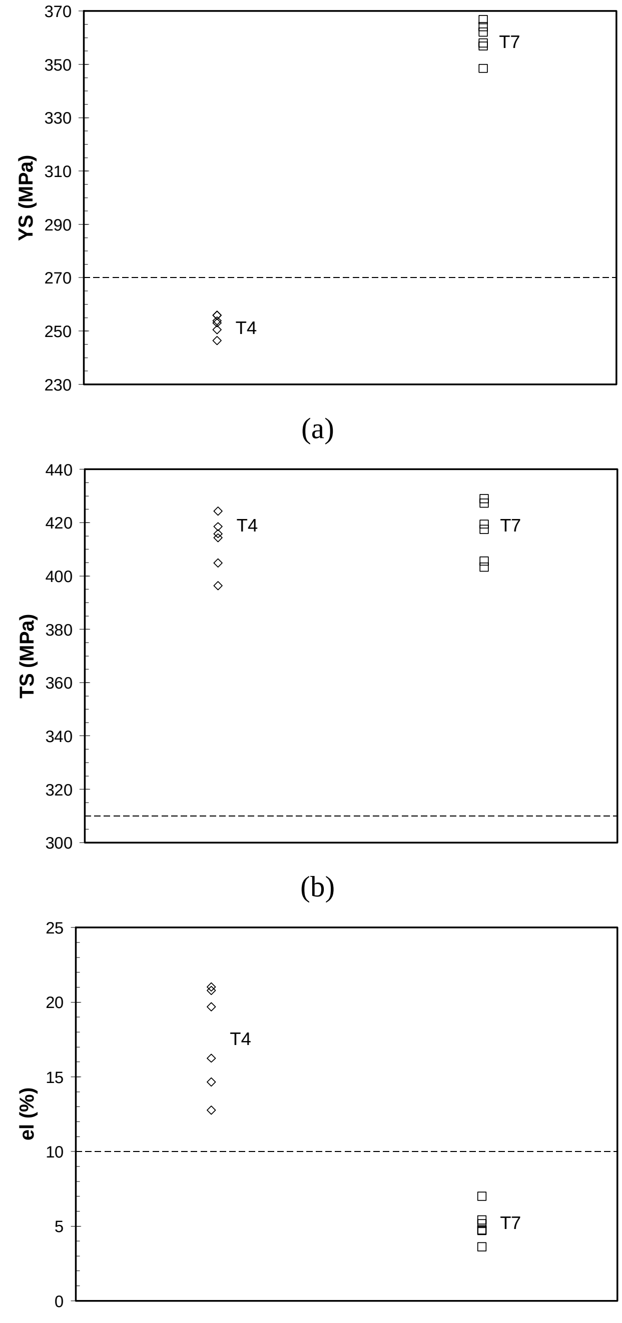


**Figure 8**. The tensile properties of semi-permanent-mold castings in T4 and T7 tempers produced by Nemak.

Two castings produced by the semi-permanent-mold process (with an Al drag) at Nemak were tested by excising tensile coupons from three locations in each casting. The tensile properties are summarized in Figure 8. The desired level of each property is indicated by a dashed line.

Note that the yield strength for T4 and the elongation for T7 tempers are barely below the desired levels. It is the believed by the entire project group that these properties can exceed the desired levels by the optimization of the heat-treatment process.

## Presentations and Publications

The results from this project so far have generated two presentations and papers:

- G.K. Sigworth, J.F. Major: "Factors Influencing the Mechanical Properties of B206 Alloy Castings", Light Metals 2006, pp. 795-799, 2006 (presented at 2006 TMS Annual Meeting)
- J.F. Major and G.K. Sigworth, "Chemistry / Property Relationships in AA 206 Alloys," paper 06-029, AFS Transactions (presented at 2006 AFS Congress).

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[i] Denotes project 405 of the Automotive Materials Division (AMD) of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR, see www.uscar.org) set up by Chrysler, Ford and General Motors (GM) to conduct joint, pre-competitive research and development.

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

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*Contractor: United States Automotive Materials Partnership (USAMP)[i]*
*Contract No.: DE-FC26-02OR22910 through the DOE National Energy Technology Laboratory*

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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 and achieve at least 15% mass reduction of the cast components.

  Note: the final engine achieved a cast-component mass reduction of nearly twice the original target.

### Approach

- Identify, benchmark, and develop a design/material property 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 as determined by the design requirements of the 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, thereby enabling more advanced powertrain applications of Mg. This will be one of the technology-transfer deliverables of the Mg 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 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)
- Conduct Mg component testing, assemble and dynamometer-test the complete engines (with the Mg components), and conduct end-of-test teardowns. Refine the cost model to support determining the cost-effective performance of the engine. (Task 6)
- Document the completed MPCC Project: work, results, lessons learned, and recommendations. (Final Report)

## 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 and 2006, substantial progress was made toward 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 FY2007 accomplishments are as follow:
- Casting of the prototype Mg cylinder blocks was completed. The blocks that passed X-ray inspection and leak testing were machined and then delivered to Gehring Corporation for application of wear-resistant coatings in the cylinder bores. Coating of the bores and finishing and honing of the blocks were completed. Ten blocks were thus successfully completed. This number is sufficient to support component and engine testing, including back-up engines for unforeseen test events.
- The machining behavior of the sand-cast cylinder block Mg alloy was observed and documented, as was that of the machining behavior of the die-casting Mg alloys used in the other components. From a machining process and materials perspective, the creep-resistant alloys comprising the MPCC engine components were indistinguishable from the well-known AM and AZ Mg alloys.
- The other Mg components (structural oil pan, front engine cover, and rear-seal carrier) were also completed and delivered to Roush Industries for use in engine testing. Friction-stir welding (FSW) was used to attach the cover to the structural oil-pan reservoir.
- The Honeywell coolant was also delivered to Roush in support of engine testing. Coolant and oil aliquots will be analyzed during dynamometer testing.
- Engine testing was begun. The first assembled engine test was successful. The test, hot scuff, is a key test of the integrity of the coating in the bores of the Mg cylinder block. In addition, the first thermal-cycle test of the assembled components was successfully completed.
- The patent application for the structural details of the Mg cylinder block was accepted by the United States Patent Office (USPTO) examiner. US Patent No. 7,284,528 was issued on October 23, 2007. It is assigned to USAMP.
- The five basic-research projects which were launched in previous years in support of the Task 3 objectives were completed. A review article about the Task 3 research was published in the August 2007 issue of the TMS Journal of Materials. The Task 3 projects are: 1) Computational Thermodynamics and Phase Equilibria (Penn State University); 2) Hot Tearing Susceptibility (CANMET – Materials Technology Laboratory (MTL)); 3) Creep Mechanisms of Mg Alloys (The University of Michigan at Ann Arbor); 4) Mg Corrosion and Corrosion Mechanisms (the Universities of Michigan at Dearborn and Ann Arbor); and 5) Recycling of Creep-Resistant Mg Alloys (Case Western Reserve University).

## Future Direction

- Excise specimens from cast Mg engine components and test to create an excised-specimen property database of the three selected Mg alloys, which database will complement the cast-specimen database completed during Phase I.
- Complete sub-assembly testing of the Mg engine components.
- Complete engine 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 project by March 31, 2008.

## Introduction

The MPCC Project will be completed in 2008. This project was launched in 2001 to realize the vision of a Mg-intensive engine that would meet OEM manufacturability and durability requirements, be cost effective, and be 15 percent lighter than the total mass of the cast Al engine components which would be converted to Mg. In the intervening nearly seven years of work, this vision remains intact. Figure 1 shows the range and depth of work accomplished by the project team.

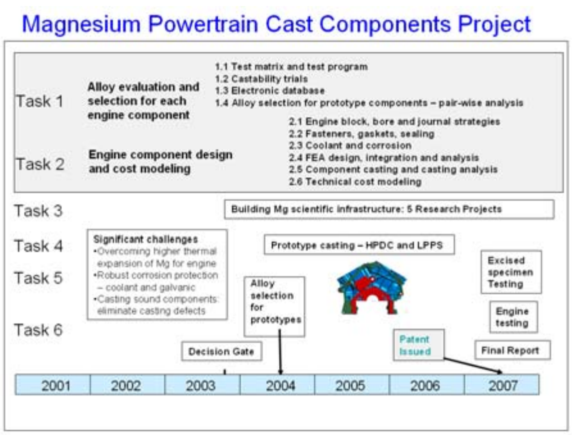



**Figure 1.** Timeline for the MPCC Project showing organization by task, milestones, and significant challenges encountered.

Beginning with an Al production engine, the Ford 3.0L V6 Duratec, the MPCC project team:
1) designed the Mg version of the engine;
2) extracted from the design, the material requirements of the "Mg-intensive engine;" 3) cast and property-tested a broad range of promising, creep-resistant Mg alloys, including sand-casting alloys for the cylinder block and high-pressure die casting alloys for the structural oil pan, front engine cover, and rear-seal carrier; 4) created technical cost models (sand casting and high-pressure die casting) for manufacturing the engine; 5) designed and built tooling to cast the engine components; 6) cast and machined the four Mg components for the engines; 7) tested two generations of ethylene glycol-based coolants which had Mg corrosion inhibitors and selected one for the engine test program; and, 8) began component (subsystem) and fully-assembled, engine-dynamometer testing of the Mg-intensive engines. Completion of component and engine testing is scheduled for the first calendar quarter of 2008.

Tasks 1 and 2, which yielded the engine design, and alloy property electronic database, have been reviewed in previous reports. Together, the successful completion of these tasks determined that it would be possible to design a Mg-intensive V6 engine and that the material properties required by the design could be satisfied with existing creep-resistant Mg alloys. These results were the basis of the successful gate review of the MPCC Project in October 2003. Phase 2 of the project commenced at that time. Task 1 created an extensive electronic database of creep-resistant Mg alloys. This database has since been combined with a complementary database of materials properties of primarily non-creep-resistant Mg alloys, generated by the Structural Cast Mg Development (SCMD) project (AMD 111) completed in 2006. The common architecture to house them was developed over the course of both projects and has been renamed the Automotive Lightweighting Materials (ALM) database. The ALM database is the core for materials properties data that will be generated in future AMD projects. The design and maintenance of this database is an area of active effort at USCAR.

Completing Task 2 required overcoming a major design challenge--that of the higher coefficient of thermal expansion (COE) of Mg relative to the other engine structural materials, Al and iron. To maintain acceptable clearance between the crank shaft and crank bore, it was necessary to use iron inserts in the cylinder block bulkheads and to replace the bedplate (lower crankcase) with bearing caps. The design resulted in the issuance of a US patent. The patent, which is assigned to USAMP, was issued on October 23, 2007. Figure 2 show a schematic of the cylinder block with the crank bore inserts and bearing caps.

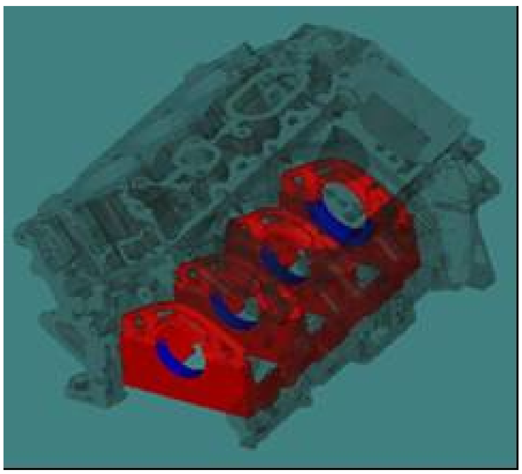


**Figure 2.** The MPCC Mg-intensive engine showing the crank-bore inserts and bearing cap assembly.

## Task 3: Basic Research in Support of Mg Powertrain Advances

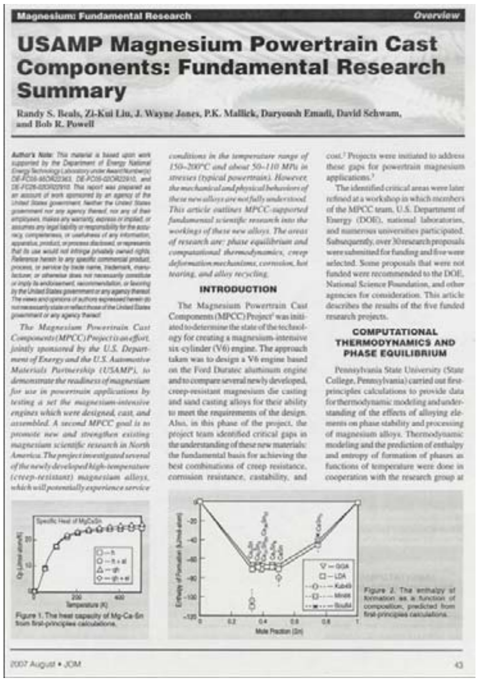
During Phase 1 of the MPCC Project, the project team identified critical scientific needs which, if not overcome, would be barriers to the production implementation of Mg-intensive powertrains. For example, an effective, Mg-corrosion-inhibited coolant was identified which will be used for MPCC engine dynamometer testing. While the coolant enables the Project test program, it is too early to predict how the coolant will perform in commercial application. Understanding corrosion performance across various test methods and how those results depended on the corrosion mechanisms and products inherent in the test would be a significant advance toward the development of robust coolants for a Mg-intensive engine. Basic research addressing the above questions was one of five MPCC/DOE-supported projects.

The research projects supported were:
1) Computational Thermodynamics and Alloy Development of Mg Alloys, under the leadership of Prof. Z.K. Liu at Penn State University; 2) Hot Tearing Behavior of Mg Alloys, under the leadership of Dr. D. Emadi at CANMET-MTL;
3) Creep, Bolt Load Retention, and Microstructural Analysis of High Temperature Mg Alloys, under the leadership of Prof. J.W. Jones at the University of Michigan at Ann Arbor;
4) Evaluation of Mg Corrosion by Various Methodologies and Surface Composition of Mg Alloys by Rutherford Backscattering, under the leadership of Prof. P.K. Mallick at the University of Michigan at Dearborn; and 5) Fluxless Recycling Methods and Process Control for Creep-Resistant Mg Alloys, under the leadership of Prof. D. Schwam at Case Western Reserve University and Dr. E. Es-Sadiqi at CANMET-MTL.

A thorough review of these completed “Task 3” projects, including citing of their publications, appeared in the August 2007 issue of JOM, a publication of The Minerals, Metals & Materials Society; see Figure 3.

## Task 4: Casting the Components for the Mg-Intensive Engine

Assembling the “bill of materials” for engine testing was completed in 2007. The bill-of-materials included the Mg cylinder blocks, oil pans, front-engine covers, rear-seal carriers, and other components that were specifically designed or selected for the engine, e.g., the head gasket, Al bolts for the pan and front cover, bearing-cap ladders assembly, Mg-protected coolant, etc. All other parts were carry-overs from the Al production Duratec. Ten such production engines were obtained to provide parts for building the Mg-intensive engines.


Magnesium: Fundamental Research — Overview

**USAMP Magnesium Powertrain Cast Components: Fundamental Research Summary**

Randy S. Beals, Zi-Kui Liu, J. Wayne Jones, P.K. Mallick, Daryoush Emadi, David Schwam, and Bob R. Powell

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*The Magnesium Powertrain Cast Components (MPCC) Project is an effort, jointly sponsored by the U.S. Department of Energy and the U.S. Automotive Materials Partnership (USAMP), to demonstrate the readiness of magnesium for use in powertrain applications by testing a set the magnesium-intensive engines which were designed, cast, and assembled. A second MPCC goal is to promote new and strengthen existing magnesium scientific research in North America. The project investigated several of the newly developed high-temperature (creep-resistant) magnesium alloys, which will potentially experience service conditions in the temperature range of 150–200°C and about 50–110 MPa in stresses (typical powertrain). However, the mechanical and physical behaviors of these new alloys are not fully understood. This article outlines MPCC-supported fundamental scientific research into the workings of these new alloys. The areas of research are: phase equilibrium and computational thermodynamics, creep deformation mechanisms, corrosion, hot tearing, and alloy recycling.*

INTRODUCTION

The Magnesium Powertrain Cast Components (MPCC) Project[1] was initiated to determine the state of the technology for creating a magnesium-intensive six-cylinder (V6) engine. The approach taken was to design a V6 engine based on the Ford Duratec aluminum engine and to compare several newly developed, creep-resistant magnesium die casting and sand casting alloys for their ability to meet the requirements of the design. Also, in this phase of the project, the project team identified critical gaps in the understanding of these new materials: the fundamental basis for achieving the best combinations of creep resistance, corrosion resistance, castability, and cost.[2] Projects were initiated to address these gaps for powertrain magnesium applications.[3]

The identified critical areas were later refined at a workshop in which members of the MPCC team, U.S. Department of Energy (DOE), national laboratories, and numerous universities participated. Subsequently, over 30 research proposals were submitted for funding and five were selected. Some proposals that were not funded were recommended to the DOE, National Science Foundation, and other agencies for consideration. This article describes the results of the five funded research projects.

COMPUTATIONAL THERMODYNAMICS AND PHASE EQUILIBRIUM

Pennsylvania State University (State College, Pennsylvania) carried out first-principles calculations to provide data for thermodynamic modeling and understanding of the effects of alloying elements on phase stability and processing of magnesium alloys. Thermodynamic modeling and the prediction of enthalpy and entropy of formation of phases as functions of temperature were done in cooperation with the research group at



Figure 1. The heat capacity of Mg-Ca-Sn from first-principles calculations.

Figure 2. The enthalpy of formation as a function of composition, predicted from first-principles calculations.

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**Figure 3.** Cover page of the review article about the MPCC basic-research projects published in the August 2007 issue of JOM.

**Cylinder Block:** Six dozen “prototype-production” blocks were sand cast by Fonderie Messier using Australia Mg Technologies alloy SC-1. Of these, half were cast during the development phase to achieve sound castings. At this point, the casting process was fixed and the remaining blocks cast. These were X-ray inspected, machined, and leak tested. Some required impregnation. The resulting set of “testable blocks” had their cylinder bores coated with a wear-resistant thermal spray. After honing the blocks, metrics were obtained for the blocks and then they were delivered to Roush Industries to await engine assembly and dynamometer testing. A partially-machined cylinder-block casting is shown in Figure 4.

**Structural Oil Pan:** Two-hundred oil pans were cast by Spartan Light Metal Products. This was a difficult component to cast, as has been described previously. Of these, about fifty were machined, leak tested, impregnated or weld repaired as necessary and delivered to Hitachi America so that the cover could be friction-stir welded on to the reservoir. A finished pan is shown in Figure 5. The welded reservoir cover, heat-staked baffle, and the cast-in groove for the gasket are evident in the figure.

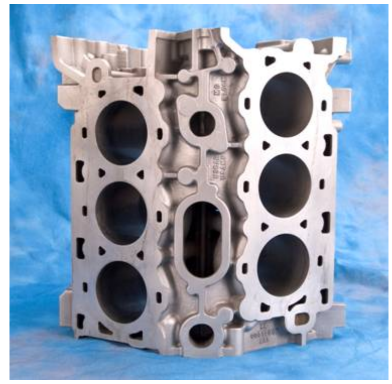

**Figure 4.** Partially-machined MPCC Mg block.

**Figure 5.** Finished, cast Mg structural oil pan.

**Front-Engine Cover:** The front-engine cover is also a difficult part to cast. Two-hundred castings were made at Intermet. These were sorted, and the sound castings machined, leak tested, and impregnated as necessary. Finished parts were delivered for engine testing during the reporting period. A finished casting is shown in Figure 6.

**Figure 6.** The MPCC Mg front-engine cover.

**Rear-Seal Carrier:** These Mg parts were thixomolded by Thixomat and delivered for engine testing in the prior reporting period. A finished casting is shown in Figure 7.

**Figure 7.** The MPCC Mg rear-seal carrier.

**Head Gasket:** Dana Corporation designed the head gasket for the MPCC Mg-intensive engine. It is a 3-layer, stainless-steel design, which contains a wave stopper sandwiched between the two active layers. Pulsator testing of the gasket validated the design and the head gaskets were manufactured and delivered.

**Mg-Protected Coolant:** Three-hundred gallons of proprietary Honeywell coolant, which was selected after a set of MPCC corrosion tests, were delivered during the reporting period.

**Fasteners:** The Mg-intensive engine used both steel and Al fasteners. The head bolts and mains were steel and the bolts for the oil pan and front-engine cover were Al. Torque testing, completed at Ford, determined that the specification for the head bolts in the Al production block could carry over to the Mg block.

## Task 5: Excised Specimen Testing for the Mechanical Property Database

Phase 1 of the MPCC Project comprised building a database of mechanical, thermo-physical, and corrosion properties of the considered sand-casting and die-casting Mg alloys. These were cast specimens. The cast-specimen database was completed and has been released in combination with that of the SCMD project data. The databases from each project reside in common architecture. This database will be housed at USCAR and will continue to be populated with properties of structural automotive materials. It will henceforth be called the Automotive Lightweighting Materials (ALM) Database.

Specimens excised from each of the four Mg components cast in the MPCC project will be tested at the results included in the ALM database. The Mg components were delivered to Westmoreland Mechanical Testing & Research. Specimen blanks were excised and then X-ray inspected at Chrysler; from these, a set of specimens will be tensile tested at room temperature and 150°C.

## Task 6: Mg-Intensive Engine Testing

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 the noise, vibration, and harshness (NVH) performance of the engine.

The MPCC test program is based on that used for the Al production Duratec. Six tests are included in the program, as is teardown analysis. The engine tests are:

- Hot Scuff
- Cold Scuff
- 150-hour Deep Thermal Cycle
- 300-hour High Speed Durability
- 480-hour Key Life Thermal Cycle
- 675-hour Engine System Test

In addition to completing the assembly of the bill-of-materials for testing, the other major effort in 2007 was acquiring and testing the necessary software, engine-control modules and other communications between the engines and the dynamometer-control systems. This major challenge was completed, a production Al engine was run to validate the dynamometer communications, and the first of the engine tests was completed.

Hot scuff is primarily a test of the bore coating and sizing of the bore, piston, and ring assembly. It was critical that we successfully complete hot scuff and cold scuff before beginning the durability tests. The hot-scuff test consisted of running the engine at 4000 revolutions per minute (rpm) for 30 minutes and then inspecting the bore walls and pistons for scratches (“scuff”). The test results were excellent. The cold-scuff engine has been assembled and is ready for testing. Engine testing is expected to be completed in the first calendar quarter of 2008. Figure 8 shows the assembled Mg-intensive engine that was used for the hot-scuff test.

**Figure 8.** Hot-scuff MPCC Mg-intensive engine.

## Conclusions

The MPCC Project has made excellent progress since its inception in 2001. In retrospect, the significant challenges for the Mg-intensive engine have been revealed to be designing for the thermal expansion coefficient of Mg, which is greater than that of Al, and casting the various components. That both challenges were overcome will be determined on the basis of the ongoing engine testing, as will the performance of the coolant-corrosion package. Progress in coolant-corrosion protection was significant, but before the Mg-intensive engine enters the commercial market, further development of robust corrosion protection is recommended.

Project objectives under the sponsorship of USCAR and DOE enabled sharing the costs and risks of this project and avoided duplication of effort by the OEM participants. The Project 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 North America. The successful completion of the Project in 2008 will add to this momentum.

## Presentations/Publications/Patents


1. R.S. Beals, Z.-K. Liu, J.W. Jones, P.K. Mallick, D. Emadi, D. Schwam, and B.R. Powell, "USAMP Mg Powertrain Cast Components: Fundamental Research Summary," published in JOM, 59, [8] 43-8 (2007).
2. P.P. Ried, B.R. Powell, W.L. Miller, L.J. Ouimet, J.F. Quinn, J.E. Allison, J.A. Hines, R.C. McCune, R.S. Beals, and L. Kopka, "Development of a Mg-Intensive Engine," presented at NADCA Chapter 39, Stevensville, MI, May 10, 2007 (R&D-10,688).
3. J.A. Hines, R.C. McCune, J.E. Allison, B.R. Powell, W.L. Miller, L. Ouimet, R.S. Beals, L. Kopka, and P.P. Ried, "Casting and Testing the USAMP Mg-Intensive Powertrain," presented at SAE World Congress, Detroit, MI, April 17, 2007 (R&D-10,688).
4. B.R. Powell, W.L. Miller, L.J. Ouimet, J.A. Hines, R.C. McCune, J.E. Allison, R.S. Beals, L. Kopka, and P.P. Ried, "Project Update: The USAMP Mg Powertrain Cast Components Project," presented at 18$^{th}$ IMA Mg in Automotive Seminar, Livonia, MI, March 28, 2007.
5. R.C. McCune, P.K. Mallick, D. Sivaraj, and Z. Shi, "Film Formation on Mg Alloys in Aqueous Solutions and Detection by Rutherford Backscattering Spectroscopy," presented and published at TMS Mg Technology Symposium 2007, Orlando, FL, March 1, 2007.
6. H. Zhang, A. Saengdeejing, J. Saal, and Z.-K. Liu, "Enthalpies of Formation of Mg Compounds from First-Principles Calculations," presented and published at TMS Mg Technology Symposium 2007, Orlando, FL, February 28, 2007.

7. J. TerBush, A. Suzuki, N. Saddock, J.W. Jones, and T. Pollock, Microstructure and Creep of Die-Cast Mg Alloys," presented at TMS Mg Technology Symposium 2007, Orlando, FL, February 26, 2007.
8. F. Hunt, H. Badarinarayan, K. Okamoto, and D. Platt, "Friction Stir Welding of Dissimilar Mg Alloys for Automotive Applications," presented and published at TMS Mg Technology Symposium 2007, Orlando, FL, February 26, 2007.
9. J.A. Hines, R.C. McCune, J.E. Allison, Bob R. Powell, W.L. Miller, L. Ouimet, R.S. Beals, L. Kopka, and P.P. Ried, "Casting and Testing the USAMP Mg-Intensive Powertrain," TMS Mg Technology Symposium 2007, Orlando, FL, February 26, 2007.
10. H. Zhang, Y. Wang, L.-Q. Chen, and Z.-K. Liu, "Thermodynamic Modeling of the Mg-Ca-Ce System by Combining the First-Principles and CALPHAD Methods," presented at Materials Science and Technology 2006, Cincinnati, OH, October 15-18, 2006.
11. D. Emadi, "Understanding Hot Tearing Behavior of Al and Mg Casting Alloys," presented at Innovation in Light Metals Casting Research Symposium, McMaster University, Hamilton, Canada, October 5, 2006.
12. Bob R. Powell, "Enabling the Mg-Intensive Engine: From the Microstructural Basis of Creep to Engine Testing," Michigan State University, Lansing, Michigan, October 5, 2006.
13. 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; 1st examiner response March 2007.


## Acknowledgements


The author would like to acknowledge the members of the AMD 304 project leadership team for their hard work in successfully completing the work to date: Randy Beals and Lawrence Kopka (retired) of Chrysler Corporation; Joy Hines, John Allison, Robert McCune (retired) of Ford Motor Company; William Miller, Larry Ouimet, and Jim Quinn of General Motors Corporation; and Peter Ried of Ried and Associates. Extensive involvement of the other members of the project team was essential and enabled this project. The member organizations are listed in Table 1.

The continuing support of our respective companies and the U.S. DOE is gratefully acknowledged.


**Table 1.** The MPCC Project Team

| | |
|---|---|
| **Core Team:** | J. Allison, R. Beals, J. Hines, L. Kopka, R. McCune, W. Miller, L. Ouimet, B. Powell, J. Quinn, P. Ried |
| **Product Design:** | Ford, GM, DCX, Magna Powertrain |
| **Alloy Suppliers:** | AMC, Dead Sea Mg, GM, Noranda, Norsk-Hydro, Solikamsk, VSMPO -Avisma |
| **Casters** | Eck, Gibbs, Intermet, Lunt, Meridian, Nemak, Spartan, |
| **Bore Treatment:** | Gehring, Flame Spray |
| **Tooling:** | Becker, Delaware, EXCO, HE Vannatter |
| **Coolants:** | Ashland/Valvoline, ChevronTexaco, Honeywell/Prestone, CCI |
| **Fasteners:** | RIBE |
| | Hitachi |
| **Gaskets:** | Dana/Victor Reinz |
| **Testing Labs:** | Amalgatech, CANMET, Stork, Westmoreland, Quasar |
| **Casting Modeling:** | EKK, Flow Science, MAGMAsoft, Technalysis |
| **Prof. Organizations:** | IMA, NADCA |
| **Project Administration :** | Ried and Associates |

[i] Denotes project 304 of the Automotive Materials 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 Chrysler, Ford and General Motors (GM) to conduct joint, pre-competitive research and development.

# C. Ultra-Large Castings of Aluminum and Magnesium (AMD 406[i])

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*Contractor: United States Automotive Materials Partnership (USAMP)[i]*
*Contract No.: DE-FC26-020R22910 through the DOE National Energy Technology Laboratory*

## Objective

- Assess the manufacturing feasibility, economics and mass reduction potential of thin-wall structural castings of aluminum and magnesium applied to automotive weight reduction.

## Approach

The Ultra-Large Casting (ULC) project builds on the findings of a U.S. Department of Energy funded contract to the American Foundry Society (AFS, Project ORNL-12401) which benchmarked various casting processes to assess their suitability to manufacture large, light-metal castings. This annual report will address three technical areas focusing on the ULC objective. These include demonstration and evaluation of two semi-solid processes the Sub-Liquidus Casting (SLC Process) for magnesium (Mg) and aluminum (Al) and a multiple hot-runner direct-injection Thixomolding process for Mg. In addition, the project has been expanded to include a study of a new Large Thin Casting (LTC) concept which examines reducing total casting cycle times by a factor of four. The SLC and Thixomolding efforts address improvements to mechanical properties while the LTC effort addresses cycle time and, hence, cost. A "real world" application of a ULC made from one of the casting processes is intended to demonstrate the weight-savings potential and other benefits of ULCs. Based on this background work and continuing research, the ULC project approach is listed below.

- Further describe and substantiate the rationale for using light-metal castings in place of conventional stamped- and welded-steel automotive body structures to reduce vehicle weight.
- The project is executed in two concurrent phases. *Phase I* is focused on process selection and capability analysis. Pha*se II* is focused on designing, analyzing and testing a "real-world" vehicle application meeting the ULC Team's criteria of a ULC.

  - The main objective for *Phase I* is to utilize the selected processes to improve the quality of cast components vs. conventional casting processes by achieving homogeneous distribution of properties and demonstrate consistent and predictable mechanical properties with improved strength and ductility.
  - The major tasks for *Phase I* will consist of Flow and Solidification Modeling, Tool Design/Analysis/Fabrication, Correlation with Casting Trials, Material Characterization, Process Capability Studies and an Economic Analysis.
  - The main objective for *Phase II* is a "Real-World" application of a ULC will demonstrate a mass reduction of 40% to 60% at a competitive cost compared to conventional steel construction. Additionally, it is desired to demonstrate parts consolidation, reduced investment cost in tooling and dies and improved energy absorption.
  - The major tasks supporting *Phase II* are finite-element analyses (FEAs) for Static, Durability, Noise, Vibration and Harshness (NVH) and Crash Analyses; System-Level and Full-Vehicle Prototype Fabrication; Durability Testing; Dynamic Crash Testing; and an Economic Analysis.
- In addition, the ULC project initiated the exploration, analytical development and engineering evaluation of a process concept to establish the process parameters and machine configurations required to produce LTCs with thicknesses as low as 1 mm at production rates of 240 pieces per hour.

## Accomplishments

<u>LTC</u>

- On a theoretical basis, the process technical feasibility of making large (e.g., automotive door inner panels) Mg and Al castings 1.00-mm thick was established.
- Determined processing requirements.
- Concepts for the engineering methods, equipment, tooling and controls necessary were developed.
- A preliminary assessment of the potential cost competitiveness of LTC castings was completed.

<u>"SLC" Process</u>

- In 2007, casting-system modifications were completed that facilitated changeover between Mg and Al. Installation included sulfur hexafluoride ($SF_6$) cover-gas distribution system and a METAMAG centrifugal pumping system to transfer Mg from the holding furnace to the bottom-pour ladle.
- The shot tip diameter was reduced from 20" to 12" diameter, improving the cycle time, casting yield, and die-temperature control.
- Initial die designs included bidirectional flow from each gate location. Preliminary casting trials revealed this gate configuration yielded inconsistent (non-repeatable) test results. The gate configuration was revised to direct metal flow through one gate in one direction only and repeatable test results were achieved.
- Integral to the test plan during the "fluidity" portion of the test sequence, the depth of the die cavity was increased from 2 mm to 3 mm by 0.5 mm increments, subsequent to evaluation of each material (A356, AM60 & AM50).
- Subsequent to completion of the "fluidity" trials, the die was reconfigured to accommodate the die inserts to manufacture the three structural shapes (waffle, structural rib & cylindrical node). The flow path from the gate to the inserts was reset to 2.5-mm depth and the profile modified from a flat plate to a C-channel, to better simulate a typical casting geometry.
- All casting trials defined in the statement of work (SOW) were completed in 2007 for both Al A356, and Mg AM60B and AM50 alloys. The designs-of-experiment (DoEs) were designed to determine the relative significance of the following process variables:
  - Metal Temperature (% solids)
  - Die Temperature
  - Vacuum (die-cavity pressure)
  - Gate Velocity
  - Casting Thickness (fluidity test only, other tests at 2.5-mm depth)
- Four die configurations were evaluated for each of the three materials:
  - Fluidity (flat plate (2 mm -> 3 mm)
  - Structural Rib (2.5-mm depth runner, C-runner)

        - Waffle (2.5-mm depth C-shaped runner)
        - Cylindrical node (2.5-mm depth, C-runner)

<u>Thixomolding Process to Produce "Shotgun"</u>

- Operation of the 4-Drop hot runner continued to improve.
- Overcame serious part-ejection problems by increased ejector pins and pin diameter, support pillars, and increased radii.
- Completed hot-runner validation effort with improved runner sequence and thermal control with improved material flow.
- Executed a DoE assessing the effects of :
    - Injection speed
    - Barrel temperature
    - Mold temperature
    - Hold time
- Alloys of AM60 and AZ91D were used to produce hundreds of samples in an effort to obtain maximum elongation preferred for structural parts. Initial trials were conducted with AZ91D with the majority of the castings produced with AM60.
- X-rays were obtained for approximately 75 shotgun and representative tensile, yield, and elongation (TYE) testes were obtained along with porosity, solids fraction, dimensional variation for numerous parts and operating conditions. Dimensional performance was found to be excellent.
- Elongation is a critical property for such structural castings and values noted at this time do not meet the 10% target. A trial is set for 1$^{st}$ quarter of 2008 to demonstrate improved elongation.

<u>Application Demonstration</u>

- Performed lateral and vertical bending tests on Mg shotguns.
- Constructed three full body-in-white (BIW) Ford F-150 cabs with all-Mg front-end structures consisting of two shotgun castings from the thixomolding process and a carry-over high-pressure die-cast (HPDC), Mg radiator support. (See Figure 8).
- Full front-end structure system-durability testing indicates the Mg shotgun equals the performance of the current steel version and weighs approximately 50% less than the steel components.

## Future Direction

<u>LTC</u>

- Prepare and present competitive analysis.
- Identify and describe future projects key to proving out feasibility of LTC concept.
- Document all findings in a "Project Close-Out Report."

<u>SLC Process</u>

- As noted, the casting trials are complete with the remainder of the work focused on:
    - Characterize the mechanical properties of the castings.
    - Completing a statistical analysis of DoE results to determine process capability.
    - Develop conclusions and recommendations for further process improvements.
- Document findings in a "Project Close-Out Report."

<u>Thixomolded Shotgun</u>

- As a result of the casting trials conducted this year, the design of the shotgun is being modified with the associated tool changes in preparation for a final trial planned for 1$^{st}$ quarter of 2008. This is expected to yield elongation values in excess of the targeted 10%.
- Parts produced during the trial in 1$^{st}$ Quarter 2008 will be fully evaluated by x-ray, TYE, and durability.
- Document all findings in a "Project Close-Out Report."

<u>Application Demonstration</u>

- Dynamic Crash Testing of Mg shotgun
- Cost Comparison Study of ULC Structure vs. Conventional Steel Structure

## The Rationale for ULCs

The majority of mass-market automobile and light-truck body structures are constructed of sheet metal stampings fastened together with resistance spot welding. This method of construction tends to increase the weight of the body because it introduces structural redundancies. For example, an outer panel requires an inner panel for stiffness, which in turn might require local reinforcements. The casting process enables all of these structural elements and features to be integrated into a single piece and, thus, has the potential to significantly reduce weight. This logic is illustrated with the example in Figure 1, which shows how a multi-piece, stamped-steel liftgate inner structure could be integrated into a single casting. There are numerous examples in the industry literature to be cited; however, the basic justification for ULCs is the ability to *reduce cost* by integrating components and *reduce weight* by taking advantage of the casting process to eliminate structural redundancies and, additionally, using lower- density material such as Mg or Al.

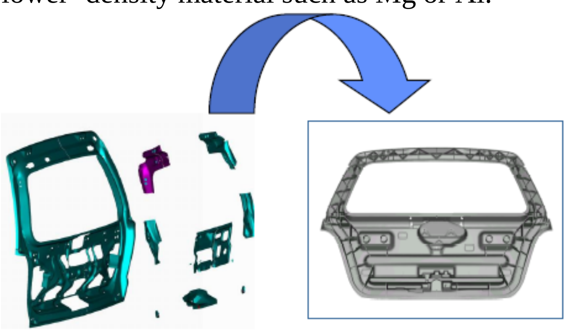


**Figure 1.** Example of parts integration.

Preliminary studies indicate large castings can be cost competitive with conventional stamped steel; however, a comprehensive, definitive case study comparing a true structural casting to conventional multi-piece stamped and welded construction has yet to be completed. Such a case study is essential for substantiating the rationale for ULCs and is undertaken by the ULC Team.

## Existing Applications of Large Light-Metal Castings

There are many examples in the industry of what are considered ULCs such as die-cast Mg instrument panel structures, seat structures, closure inner structures, etc. However, it is more appropriate to describe these applications as quasi-structural because they are not totally integrated into the body structure. These quasi-structural components demonstrate the lightweighting potential of large castings replacing conventional stamped steel structures.

A notable example of an ultra-large structural casting is the current Ford F-150 radiator support structure. It is a one-piece, thin-walled Mg casting (see Figure 2) that replaces seven major stamped steel parts for a 25 lbs. weight savings. It is integrated into the body structure where it contributes to torsional stiffness and plays a role in crash. If applications of ultra-large structural castings like the F-150 radiator support and other large quasi-structural parts already exist, why is there a need for an ULC project?


**Figure 2.** Cast Mg radiator support.

These particular components are manufactured using the conventional HPDC process, which has some inherent limitations in achieving consistent mechanical properties.

## Current Manufacturing Processes for Producing Large Light Metal Castings

The F-150 radiator support and most large quasi-structural automotive light-metal castings are manufactured with the HPDC process. While they perform adequately in many applications, HPDCs may not be suitable for other primary structures like pillars, rails or bodysides that have to manage large amounts of crash energy. HPDCs lack the level of ductility and other desirable mechanical properties for these structural applications. Therefore, further uses of HPDCs beyond today's applications are limited by the process capabilities and by the mechanical properties achievable with conventional die-casting.

Utilizing a relatively simple process such as HPDC to make structural parts is highly desirable by the industry. Unfortunately, the presence of porosity in HPDCs has a detrimental effect on mechanical properties. A plethora of countermeasures have been developed to combat porosity (and other shortcomings) of the HPDC process by introducing into the process vacuum, non-turbulent filling of the shot sleeve, and "squeezing" during solidification. There are also expensive, specialty, heat-treatable alloys that are used along with one or more of the countermeasures to lower porosity levels and improve quality, but not without significant increase in cost. In spite of these enhancements and spin-off HPDC-based processes, HPDCs continue to be challenged by tradeoff between quality and cost. This inhibits the wide use of HPDCs as primary structural parts.

Besides porosity and non-uniform mechanical properties, adapting HPDC to ULCs presents other challenges such as low yield. In some cases, over 50% of the shot weight consists of biscuits, runners and overflows. This has an effect on economics, especially for Mg die-castings since Mg is not able to be recycled in-process. As casting size increases, runner systems become larger and more complex, increasing tooling cost and necessitating the use of larger tonnage die-casting machines. This significantly increases the cost of capital equipment.

## LTCs

There have been significant developments in die-casting machines and processes over the past 30 years (1975 – 2005). Nearly all of that development has focused on making castings that are more structurally sound. Squeeze casting and several semi-solid processes such as "thixocasting", Thixomolding™ and "rheocasting" are examples.

There have been a few examples of moderately - large thin castings but large, thin (1 mm) Al castings have not become common in the marketplace. Thin Mg castings (such as cellular telephone housings) are common, but they are small. The design freedom intrinsic with castings leads one to believe that there must be a market for large, thin Al and Mg castings if they can be made with a consistently high quality and at a low-enough cost.

This is not a study of the costing and pricing dynamics of the industry. If the castings can be made one-millimeter thick and cast at 240 castings per hour from a single cavity die, requirements for mass reduction and cost parity should be satisfied.

A casting process concept has been proposed and this engineering evaluation is to determine its technical and economic feasibility. For demonstration, a large, thin panel (e.g., pickup truck door inner) was chosen for a full analysis.

The procedure follows the North American Die Casting Association (NADCA) 23-step ***"Process Engineering and Design for Die Casting"*** flow chart. Questionable, missing data and physical relationships are identified. Concept designs for a casting-machine die and work cell to meet the processing requirements are created and will be described in the NADCA paper[1]. Following this engineering analysis, the economics of operation are developed.

Finally, detailed descriptions of possible follow-on projects were developed and are described in a separate section of this report. At this point, the following conclusions can be stated:

- It is feasible to pressure-cast components having a projected area of one square meter and a substantial area having a thickness of one millimeter. A door inner for a full-size pickup truck is an example.
- Such panels can be cast at a rate of 240 per hour.
- High investment cost and unproven technology are significant barriers.

- Cost model shows that such castings may be cost competitive with stamped-steel, door-inner panels.
- Direct material remains the largest single cost factor accounting for over half of the part cost without considering the amortized cost of tooling.

**SLC Process Development/Demonstration**

Although the SLC process has been described in previous annual reports, some review is provided here. It is a unique process that offers the potential to produce thin-wall Al castings having greater properties (i.e., no heat treatment) than typically achieved by conventional sand, permanent-mold or die-casting processes. The THT hardware system offers the possibility to operate as many as four injectors; thus, the metal flow length can be kept low while producing large parts. The machine operates as a vertical casting machine at elevated pressures with the injectors providing metal with a vertical stroke. The time that molten metal is held in the injector determines the solid fraction of metal injected.

### SLC Approach

To conduct this evaluation, a test part was designed that met the following criteria:

- Producable on an existing 1000-ton machine
- Part reflects the flow length for a ULC
- Part casting features/challenges are representative of a structural ULC
- Enables the assessment of knit-line quality
- Same tool set can be readily used for fluidity (Figure 3) test, part geometric features of rib section (Figure 4) and step (waffle) section (Figure 5) and knit-line node (Figure 6) evaluation
- Fluidity picture frame (Figure 3) measures 395 mm by 395 mm
- Flow length from gate thru the rib section (Figure 4) is 580 mm and the same holds for the step section. For example, the metal flows from the gate thru the grid section and exits the grid section after flowing approximately 580 mm.
- Flow length from the gate to the far side of the knit-line node is approximately 530 mm. The node is a cylinder 50-mm high with a 63.5-mm inner diameter (ID) and 6.5-mm wall. NOTE: the runners for the grid, step and node are primarily a U-section with the width 53.6 mm, height 40 mm, and nominal wall thickness of 3 mm.

**Figure 3.** Fluidity test part.

**Figure 4.** Rib geometry.

### SLC Experimental Results

The flow length was conducted first. The total flow length for the fully-filled part is in excess of 1.5 m. The sides of this fluidity picture frame measures 395 mm square (Figure 3).

With respect to fluidity (Figure 4), a DoE was conducted with the following results:

- Primary variables were determined to be gate velocity (flow turbulence & fill time), die temperature, and section thickness.
- Secondary variables were determined to be metal temperature and vacuum level.

With respect to part geometries (see Figures 5 and 6) quality (x-ray), a DoE was conducted with the results summarized:

- Primary variables are gate velocity (lower velocity is better) and vacuum level
- Secondary variables are metal temperature, section thickness and die temperature.

**Figure 5.** Waffle geometry.

**Figure 6.** Knit-line node geometry.

For the above tests, the die lubricant was found to significantly impact the test results. Casting quality noted by x-ray appears to degrade as the distance from the ingate increases and the ingate velocity increases and this is particularly true following a change in flow direction. The simulation results were confirmed with the actual testing trials.

**SLC Conclusions**

- Low flow velocity and short flow distances, thus, hot-runner technology (Mg) and multiple in-gates for Al are desirable for quality parts
- Stable die temperatures yield consistent casting quality and reduced process scrap.
- Elevated die temperatures enable manufacture of components having reduced cross-section.

The remaining effort will include:

- Property determinations
- Process assessment for Al and Mg parts with economics
- Project Close-Out Report

## Thixomolded Shotgun

G-Mag is modifying tooling in preparation for one more casting trial utilizing the Thixomolding process to produce a Mg shotgun. The Thixomolding process has the potential to produce Mg ULCs with properties compatible with structural applications at costs competitive with steel components. The effort exploits the semi-solid process licensed by Thixomat, Inc. of Ann Arbor, Michigan. It can be best described by its similarity to plastic injection molding. Mg is prepared in chip form and supplied to the casting machine where the chips are partially melted and injected into the mold cavity.

To evaluate and develop the process, a shotgun for a Ford F-Series vehicle was chosen. The shotgun (see Figure 7) joins the A-pillar to the radiator support structure. The radiator support structure is a Mg casting produced by the HPDC process. For such a part, a full evaluation of the component can be conducted.
Before 2007, the part design and the tooling was evaluated by FEA and casting simulations and reported in the annual report for 2006. The major part of the activity for 2007 involved actual casting trials.

**Figure 7.** F-Series "Shotgun."

**Figure 8.** Full-cab with Mg shotguns.

### Casting Trials

A DoE was performed to determine optimized process settings. Various factors including injection speed, melt temperature, shot size and mold temperature were reviewed extensively. The best parameter values were chosen based upon part appearance. For example, 100% part appearance is completely filled, no visual cold flows, no holes in the ribs, no underfill, no sink marks, no cracks, no distortion and no warpage. The other extreme (0%) is a part with voids, cold flows, underfill areas, cracks, distortion, broken ribs, warpage, and non-uniform fill due to blocked gates.

### Thixomold DoE

A Taguchi DoE design was conducted with L8 table having 6 factors and 2 values.

The nominal parameters are:

- AM60 material
- Injection Machine-Husky Hydroelectric 1000t
- Hot runner, 4-drop shotgun tool

### DOE Parameters

- Metal Temperature (1120$^o$F, 1145 $^o$F)
- Mold Temperature (400$^o$F, 500$^o$F)
- Injection Speed (3 m/s, 6 m/s)
- Hold Pressure (500 psi, 1000 psi)
- Hold time (0.5 s, 1.0 s)
- Cool time (20 s, 30 s)

Based upon the part appearance criterion, the following was concluded:

- Injection speed, melt temperature and mold temperature have the greatest impact
- Holding pressure and cooling time have minimal impact on part appearance.

### Dimensional Variation

Fifteen lefts and fifteen right shotguns were randomly selected and examined dimensionally with the following information:

- The overall length varied from 843.67 mm to 845.510 mm (i.e., less than +/- 1 mm)
- An important hole-to-hole spacing varied from 353.756 mm to 354.518 (i.e., less than +/- 0.5 mm)

In addition, parts were checked for distortion or flatness. Again, parts were selected randomly and found to be flat within an average of 0.044 mm with a max of 0.091 mm and a minimum of 0.007 mm.

### Tensile, Yield and Elongation

TYEs were measured for a large group of parts with elongation as high as 17% with an average of approximately 5% in the areas evaluated. Representative yield and tensile strengths are 18 ksi and 27 ksi, respectively. It was the goal to achieve a 10% elongation over much of the part area, but this has not been achieved.

**Porosity**

In area of the buckling zone, the solid % was determined to be an average value of 6% solids (4.22% to 7.99%) with an average porosity of 0.77% (0.51 to 1.04 %) established by Archimedes method.

**Full Component Durability Test**

Ford conducted a durability test on a shotgun selected at random with its life exceeding that of the steel shotgun being used today. The Mg shotgun weighed approximately half that of the steel part.

## Conclusions

As a result of the effort expended this year the following conclusions are provided:

- Dimensional control was very acceptable.
- The critical property of elongation fell short of expectations (i.e., seeking 10%). Changes in the part design are being made that are expected to result in a 10% elongation.
- Solids content varies significantly over a relatively small area of the part and around the same drop.

## Future Direction

As a result of the evaluations reported, the part design was modified with casting simulations currently underway. The tooling will be subsequently modified and another series of castings will be produced for evaluation. Again, these changes are expected to result in the desired 10% elongation.

## Presentations/Publications/Patents

1. Edmund Herman, *USCAR/USAMP Large-Thin Casting Project*. NADCA/AFS 112th Metalcasting Congress at CastExpo '08, May 17, 2008, Atlanta, GA.
2. Ultra Large Casting (USCAR) "Shotgun" awarded 1st Place in the Process Category, IMA 2007 Awards Competition, May 15, 2007 Vancouver, BC.
3. Michael Maj, *Ultra-Large Castings for Lightweight Vehicle Structures*, IMA Automotive Seminar, March 28, 2007, Laurel Park Manor, Livonia, MI.
4. Michael Maj, *Ultra-Large Castings for Lightweight Vehicle Structures*, TMS 2007 Annual Meeting, 2/21 thru 3/1, Orlando, FL.

## References

1. Edmund Herman, *USCAR/USAMP Large-Thin Casting Project*. NADCA/AFS 112th Metalcasting Congress at CastExpo '08, May 17, 2008, Atlanta, GA.

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[i] Denotes project 406 of the Automotive Materials 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 Chrysler, Ford and General Motors (GM) to conduct joint, pre-competitive research and development.

# D. High-Integrity Magnesium Automotive Castings (HI-MAC) (AMD 601[i])

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*Contract No.: DE-FC26-020R22910 through the DOE National Energy Technology Laboratory.*

## Objective

- Develop and validate casting-process technologies needed to manufacture squeeze- and low-pressure-cast magnesium (Mg) automotive suspension components.
- Address critical technology barriers inhibiting Mg application and component affordability.
- Deliver components for static and/or vehicle testing.
- Evaluate potential of emerging Mg-castings technologies.

## Approach

- The approach of the HI-MAC project is to develop the metal-casting-process technologies necessary to cost-effectively manufacture high-integrity (high ductility and strength, low porosity, free of objectionable oxides and inclusions), cast Mg automotive-chassis components.
- This project will develop existing aluminum (Al), low-pressure permanent-mold and squeeze-casting processes for the production of Mg structural castings.
- The project aims to facilitate production of Mg components requiring geometries and properties not possible with existing high-pressure die-casting (HPDC) process limitations.
- Two new emerging casting processes (ablation and T Mag) will be investigated.
- The project will also develop enabling technologies critical to increased cast-Mg automotive applications—microstructure control, porosity and hot-tearing computer models, thermal treatments, and controlled mold filling.

## Accomplishments

- Cost expenditures match original budget numbers and in-kind support meets or exceeds forecasted numbers.

- The HI-MAC Project team has 46 active participants from Chrysler, Ford, General Motors (GM), other industrial firms and academia.
- All project participants support the project functions including visits to project member's facilities and universities; participation in conference calls and quarterly review meetings (QRMs).
- Four, new, Mg-casting processes have been and are being developed. Rear lower control arms have already been produced from two of the processes.
- Seven different universities are actively involved in the HI-MAC project, including students from undergraduate to PhD levels.
- Microstructure properties and modeling techniques are being identified for the different types of Mg alloys that have already been cast.
- The *Magnesium Vision 2020 Document* (developed by the previous Structural Cast Magnesium Development [SCMD] project) is used as reference by the HI-MAC Project Team as the new Mg-casting processes are developed.

## Future Direction

- Accomplishment of the four, new, Mg-casting processes will provide industry with higher-integrity, Mg, automotive castings that can be manufactured at a more economical initial set-up cost than is currently used by industry.
- The HI-MAC Project Team will provide Mg castings from two of the four new casting processes by year-end (YE) 2007 for testing and evaluations (Figure 2).
- Complete all statement-of-work (SOW) tasks in accordance with the original project timeline and budget figures.

## Introduction

The overall introduction for this project has not changed since the original SOW was established. However, as each report is submitted to the Department of Energy (DOE), various aspects within the Introduction will be mentioned as progress is made in the completion of tasks. Perhaps the quickest, near-term path to increased Mg content in automobiles is through increased use of metal castings, and the HI-MAC Project is well on its way to support this goal.

HI-MAC addresses the near- and mid-term metal-casting development needs identified in the published document, *Magnesium Vision 2020.* Understanding and eliminating the technical barriers that currently inhibit Mg-casting production will move the automotive industry into a better position to realize emerging automotive Mg-component needs, build needed Mg-industry infrastructure and develop tools that will be needed to reduce the cost of Mg components and enable sustainable production requirements. The HI-MAC Project has already started to address these three key issues:

**Development of Casting Tools:** Develop technologies and tools that will be required for sustainable, long-term procurement of cast-Mg automotive-components (Tasks 3, 4, 5 and 6). These tasks will address the science and technological barriers that currently inhibit production and affect the affordability of cast-Mg components.

**Casting Process Development:** Develop casting processes to facilitate production of cast-Mg automotive chassis components that cannot be manufactured using current process limits (Tasks 1, 2 and 7). A new squeeze-casting cell (Figure 1) has already been built and is in operation by Contech, one of the HI-MAC Project participants.

**Figure 1.** Contech squeeze-casting cell.

A similar, low-pressure casting cell was also built (Figure 2) and Mg control-arm castings have already been produced (Figure 3).

**Figure 2.** CMI Equipment and Engineering low-pressure casting cell.

**Figure 3**. Mg control arm.

**Infrastructure Development:** Development of casting processes (Figures 1 and 2) and tools will include industry participation by automotive suppliers currently producing Al components (Tasks 1, 2, 7), the development of equipment uniquely suitable for the production of Mg components (Task 2, 6) and development of a broader research and science base (Tasks 3, 4, 5, 8).

New casting processes and tool development will be demonstrated by production of a Mg control arm by low-pressure cast, squeeze-cast, and newly-emerging casting processes. Control arms will be delivered for static and/or vehicle testing. To support the achievement of these processes, the project is divided into eight tasks to address key technology barriers that limit cast-Mg, automobile suspension and chassis applications and affect the manufacturing costs of these components as they are defined today:

**Task 1:** Squeeze-casting process development

**Task 2:** Low-pressure casting process development

**Task 3:** Thermal treatment of castings including research into stepped heat-treatment and fluidized beds

**Task 4:** Microstructure control during casting including grain refining and property improvement

**Task 5:** Computer modeling and properties to enable prediction of casting quality and microstructure

**Task 6:** Controlled molten-metal transfer and filling

**Task 7:** Emerging casting technologies

**Task 8:** Technology transfer Steering Committees have been formed to independently assist the Core Project Team in the achievement of these tasks.

## Conclusions

The HI-MAC project addresses the critical barriers to Mg casting implementation, as stated in the *Magnesium Vision 2020* document. The four new casting processes will provide industry with higher-integrity, Mg, automotive castings for applications such as control arms, knuckles, and wheels that may ultimately enable weight savings of 35 to 60%. The new enabling technologies will reduce Mg-component processing and facility costs and enable the production of high-integrity Mg castings. The use of controlled, molten-metal transfer and filling (electromagnetic pump) will eliminate many of the production and environmental issues associated with the standard cover gas over Mg melts and yield higher-quality castings. In addition to all of the above, the HI-MAC project will provide technical support to the Magnesium Front End Research and Development Project (AMD 604. See 6.B/).

## Presentations/Publications/Patents


1. Beckerman,C., Prediction of Porosity and Hot Tears in Magnesium Castings at Materials Science and Technology (MS&T)2007 Conference, Detroit, MI September 2007.
2. Xue,Y., Horstemeyer, M., McDowell, DL., El Kadriri, H., Fan, J., Microstructure-based multistage fatigue modeling of cast AE44 magnesium alloys, Int J of Fatigue 2007; 29:666-76.
3. El Kadiri, Xue, Y., Horstemeyer, MF, Jordan, B., and Wang, P., Fatigue Crack Growth Mechanisms in a Die Cast AM50 Alloy, Acta Materialia 2006; 54:5061-76.
4. Low-Pressure Casting of Magnesium Alloys for Automotive Components; Greg Woycik, CMI Equipment & Engineering; American Foundry Society-111th Metalcasting Congress, May 15-18, 2007.
5. Magnesium Casting Technology Update; David Weiss, Eck Industries, Inc.; American Foundry Society-111th Metalcasting Congress, May 15-18, 2007.
6. HIMAC; Magnesium Squeeze Casting Update; Brian Szymanowski, Contech; American Foundry Society-111th Metalcasting Congress, May 15-18, 2007.
7. High-Integrity Magnesium Automotive Components (HI-MAC); Bruce Cox, Chrysler NA, American Foundry Society-111th Metalcasting Congress, May 15-18, 2007.


## Acknowledgements

Within 14 months after project approval, the HI-MAC Project team had cast three Mg castings from three new casting processes. This success would not have been possible without the support and help from: the DOE; the USAMP Steering Committee; the USAMP AMD Board; Chrysler, Ford and General Motors; the other-industrial and academia support teams; the Canadian and US National Labs. In addition, the USCAR Office and American Foundry Society staff members were available to assist our Project Team during monthly and quarterly review meetings that were held at their respective facilities. The Project Chairmen appreciates the support from all of the teams mentioned above.

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[i] Denotes project 601 of the Automotive Materials Division (AMD) of the United States Automotive Materials Partnership (USAMP), is one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by Chrysler, Ford and General Motors (GM) to conduct joint, pre-competitive research and development. See www.uscar.org.

# E. Casting/Solidification of Magnesium Alloys

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*Contract No.: 4000054701*

## Objective

- Identify the root causes for porosity, segregation, and other defects in magnesium (Mg) cast parts and propose practical solutions for the improvement of casting processes.

## Approach

- Mg-alloy cast parts are gaining increasing attention from the automotive sector, aiming at weight saving. However, the casting of Mg alloys is still plagued with problems that are difficult to solve: porosity, macro-segregation, oxide entrainment, irregularity of microstructure, corrosion, machining safety, etc. This research project addresses the fundamental behavior of solidification phenomena that lead to undesired defects (e.g., porosity, macro-segregation, mushy zone) in Mg cast parts, with the objective of developing new or improved casting methods for these alloys.

## Accomplishments

- Task 1 – Add pore nucleation and growth models to MULTIA solidification simulator. Completed. Model validated with A356; validation with AZ91 coming next. Results presented at 2007 American Foundry Society (AFS) and The Minerals, Metals and Materials Society (TMS) conferences.
- Task 2 – Upgrade MULTIA with an ORNL algorithm for coupled micro-porosity and interdendritic flow. 70% completed. A MSST Master of Science (MS) student is working in the project.
- Task 3 – Perform measurement of density and permeability in mushy zone of Mg alloys. 50% completed. Density measurement to be performed at High-Temperature Materials Laboratory (HTML). Samples of AZ91, AM60, and AE44 are being prepared. Permeability will be determined with indirect method from measurement of cooling rate and dendrite-arm spacing in cast samples made at ORNL. Cast ingots of various sizes were made of AM60B and AZ91D, with measurement of cooling curves. Additional die-cast samples of AE42, AE44, and AM50 were also sent to MSST. Characterization is in progress.
- Task 4 – Perform thermodynamic calculations of physical properties of Mg alloys. 20% completed. Curves of temperature (T) vs. fraction liquid calculated at ORNL for AM60B, AZ91D, AE42, AE44 and AM50. MSST just purchased ThermoCalc Mg database. Calculations of other physical properties are in progress.
- Task 5 – Apply MULTIA to simulate porosity and segregation in Mg-alloy castings. To be started once a full data set can be obtained. First alloy to be simulated will be AZ91, then AM60 and AE44.
- Task 6 – Perform validation experiments for Mg-casting simulations. Scheduled for year two, but we are gathering literature experimental data on AZ91 to validate several aspects of the model.

## Future Direction

- Task 1 – Validate model with permanent-mold (PM) castings of AZ91, AM60 and AE44.
- Task 2 – Task to be completed by end of 2007.
- Task 3 – Supply round bar samples of AZ91, AM60 and AE44 to HTML for measurement of density in mushy zone, specific heat and thermal diffusivity (collaboration of A. Sabau and W. Porter, ORNL). MSST to characterize Mg-alloy samples made at ORNL for determination of permeability (collaboration of Q. Han, Purdue Univ.).
- Task 4 – Finish thermodynamic calculations of properties of AZ91, AM60 and AE44. Assemble a complete MULTIA data set for these alloys, obtaining remaining properties from experiments or literature.
- Task 5 – Perform simulations of segregation and porosity formation for the above alloys in PM casting.

## Project Staffing Overview

After visiting us for an invited seminar in the last week of March, Prof. William Griffiths (University of Birmingham, UK) has just returned to MSST for a sabbatical leave. He will spend four months working with us. Professor Griffiths has an extensive experience in Mg alloys and oxide films defects, and he will be a valuable support to the project. A section summarizing his recent research on oxide bifilms in Mg castings is included in this report.

Graduate students Sandeep Poola and Hebi Yin have been recruited for the project. Sandeep (MS student) spent two weeks at ORNL working with Dr. Qingyou Han on casting of Mg-alloy samples for determination of permeability. Hebi (Ph.D. student) is developing a cellular automaton model for calculation of solidification microstructure in Mg alloys. Ph.D. student Claudio Pita is developing a meshless method for simulating the dynamics of oxide bifilms, under our National Science Foundation (NSF) project "Modeling of oxide bifilms in aluminum castings." A new Ph.D. student, Udaya Sajja, has recently joined this project.

Sergio Felicelli attended a High-Integrity Magnesium Automotive Casting (HI-MAC. See 3.D) quarterly report meeting in March 2007 at the AFS headquarters to stay informed on the progress in that project directly related to ours. We continue monitoring their progress through access to the HI-MAC viewroom.

Dr. Felicelli contacted Prof. Jeff Wood at University of Western Ontario to become informed of their work for the AUTO21 initiative. Though their research has been in the area of high-pressure die casting (HPDC), a potential collaboration link was established.

We purchased a license of thermodynamic software ThermoCalc, plus additional licenses for the steel, aluminum (Al) and Mg databases. Training on the software was held on site for several researchers of the ORNL/MSST project.

Graduate student Enrique Escobar de Obaldia, who worked in the porosity model development, graduated in May 2007 with a MS degree and is now a project engineer at MAGMA Foundry Technologies, IL.

## Modeling the Onset and Evolution of Hydrogen Pores During Solidification

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### Abstract

A quantitative prediction of the amount of gas microporosity in alloy castings is performed with a continuum model of dendritic solidification. The distribution of the number and size of pores is calculated from a set of conservation equations that solves the transport phenomena during solidification at the macro-scale and the hydrogen diffusion into the pores at the micro-scale. A technique based on a pseudo-alloy solute which is transported by the melt is used to determine the potential sites of pore growth, subject to considerations of mechanical and thermodynamic equilibrium. Two critical model parameters are the initial concentration of the pseudo-solute and the initial size at which pores start to grow. The dependence of the model prediction on these parameters is analyzed for Al A356 plate castings and the results are compared with published experimental data.

### Introduction

Although porosity occurring during alloy solidification is very harmful to the mechanical properties of alloys, the control or elimination of this defect is still a formidable task in modern foundries. The formation of microporosity in particular is known to be one of the primary detrimental factors controlling fatigue lifetime and total elongation in cast Al components [Major, 1997]. Microporosity refers to pores which range in size from micrometers to hundreds of micrometers and are constrained to occupy the interdendritic spaces near the end of solidification. The micropores can form due to microshrinkage produced by the pressure drop of interdendritic flow or because of the presence of dissolved gaseous elements in the liquid alloy. In this work, we focus on the calculation of gas microporosity and, unless noted otherwise, we use the term porosity to mean gas-induced microporosity. In the case of Al alloys, hydrogen is the most active gaseous element leading to gas porosity [Felicelli, 2000]. Many efforts have been devoted to the modeling of porosity formation in the last 20 years, particularly in Al alloys [Felicelli, 2000, Han, 2002, Lee, 2001, M'Hamdi, 2003, Poirier, 2001, Zhu, 2005] and, in a lesser degree, to nickel superalloys [Felicelli, 2000, Guo, 2003] and steels [Carlson, 2003, Sung, 2002]. More recently, rather sophisticated models have been developed to include the effect of pores on fluid flow (three-phase transport) [Sabau, 2002], multiscale frameworks that consider the impingement of pores on the microstructure [Lee, 2004], and new mechanisms of pore formation based on entrainment of oxide bifilms [Yang, 2004]. A recent review on the subject of computer simulation of porosity and shrinkage related defects has been published by Stefanescu [Stefanescu, 2005].

## Mathematical Model

The model presented here is based on a robust and well-tested, multicomponent solidification program that calculates macrosegregation during solidification of a dendritic alloy with many solutes [Felicelli, 1998]. The model (named MULTIA) solves the conservation equations of mass, momentum, energy, and each alloy component within a continuum framework in which the mushy zone is treated as a porous medium of variable permeability. In order to predict whether microporosity forms, the solidification shrinkage due to different phase densities, the concentration of gas-forming elements and their redistribution by transport during solidification, were later added to the model [Felicelli, 2000]. In this form, the model was able to predict regions of possible formation of porosity by comparing the Sievert's pressure with the local pressure, but it lacked the capability of calculating the amount of porosity. This model has already been presented in detail in [Felicelli, 2000] and [Felicelli, 1998], and references therein; only the main assumptions and governing equations are presented here. In particular, we discuss a method that adds to MULTIA the capability of calculating the volume-fraction of porosity and the pore-size distribution during solidification. In this method, the growth of pores is simulated with a micro-scale growth model that is coupled to the macro-scale governing equations in MULTIA. The criterion for the formation of pores is based on equilibrium conditions between the pores and the alloy and on the transport of a pseudo-solute that represents inclusions or impurities dissolved in the alloy. The pore volume fraction as well as the pore-size distribution can be determined from the evolution of the population and size of pores during solidification.

Governing Equations

The following assumptions are invoked: the liquid is Newtonian and the flow is laminar; the Boussinesq approximation is made in the buoyancy term of the momentum equation; the solid phase is stationary; the gas phase does not affect the transport equations (two-phase model); and the densities of solid ( $\rho_s$ ) and liquid ( $\rho_l$ ) are different but constant. Additional assumptions are made at appropriate places in the article. With these assumptions, the conservation equations can be written as [Felicelli, 2000]:

Mass and momentum:

$$\nabla \cdot \mathbf{u} = \beta \frac{\partial g_l}{\partial t} \tag{1}$$

$$g_l \frac{\partial}{\partial t}\left(\frac{\mathbf{u}}{g_l}\right) + \mathbf{u}\cdot\nabla\left(\frac{\mathbf{u}}{g_l}\right) = -\frac{g_l}{\rho_l}\nabla p + \frac{\mu}{\rho_l}\nabla^2\mathbf{u} - \frac{\mu}{\rho_l}\frac{g_l}{\mathbf{K}}\mathbf{u} + \frac{\mu\beta}{3\rho_l}\nabla\left(\frac{\partial g_l}{\partial t}\right) + \frac{\rho\, g_l}{\rho_l}\mathbf{g} \tag{2}$$

Energy:

$$\overline{\rho c}\frac{\partial T}{\partial t} + \rho_l c_l \mathbf{u}\cdot\nabla T = \nabla\cdot\overline{\kappa}\nabla T - \rho_s\left[L + \left(c_l - c_s\right)\left(T - T^H\right)\right]\frac{\partial g_l}{\partial t} \tag{3}$$

Solutes:

$$\frac{\partial\overline{\rho C}}{\partial t} + \rho_l \mathbf{u}\cdot\nabla C_l = \nabla\cdot\overline{\rho D\nabla C} - \beta\rho_l\frac{\partial g_l}{\partial t}C_l \tag{4}$$

In the above equations, **u** is the superficial velocity, $g_l$ is the volume fraction of liquid, *t* is time, ρ is density, β is the shrinkage coefficient $\beta = \left(\rho_s - \rho_l\right)/\rho_l$ , *p* is pressure, μ is viscosity, **g** is gravity, **K** is the permeability, *T* is temperature, *c* is specific heat, κ is the thermal conductivity, *L* is latent heat, $T^H$ is a reference temperature, *C* is the solute concentration in weight per cent, and *D* is solute diffusivity. The subscripts *"s"* and "*l*" refer to solid and liquid, respectively, while a bar over a variable means a volume average of the variable over the solid-plus-liquid mixture; for example, $\bar{\rho} = g_l \rho_l + g_s \rho_s$, where $g_s$ is the volume fraction of solid. Several equations (4) are solved in the model, one per each solute. A particular solute is hydrogen, which can precipitate in gas form when its dissolved concentration in the liquid exceeds the solubility at the local temperature and pressure. The energy and solute equations are rearranged in modified form depending whether the solute is assumed to have negligible or complete diffusion in the local solid (like hydrogen). [Felicelli, 2000] and [Felicelli, 1998] provide more specific details on the model regarding additional rearrangement of equations and numerical solution procedures.

Calculation of Porosity

A pore-growth model is implemented at the microscopic scale together with a criterion for nucleation of pores. The term nucleation is here used in the general sense to refer to the origination of pores, without necessarily implying any particular mechanism of classical nucleation. We assume that, dispersed in the liquid, there is an initially-known distribution of microscopic inclusions. These can be oxide bifilms that were entrained during melt pouring, old oxide bifilms that existed in the melt before pouring, or other impurities that serve as possible nucleation sites for hydrogen pores. We call $n(\mathbf{x},t)$ the number of these inclusions per unit volume of alloy, where $n(\mathbf{x},0)$ is known. The inclusions are transported with the velocity field **u** of the liquid, and they can partition to the solid like the other solutes of the alloy. For implementation purposes, the inclusions are treated as another alloy solute with negligible diffusion.

We assume that hydrogen pores can nucleate and grow only at places where the following two conditions are met:

$$n > 0 \tag{5a}$$

$$p + \frac{2\sigma}{r} < p_S \tag{5b}$$

in which $p_S$ is the Sievert pressure [Flemings, 1974], $r$ is the pore radius and $\sigma$ is the surface tension of the pore-liquid interface. Most of the mechanisms that have been proposed for the nucleation of pores are based on the size of interdendritic cavities and the theory of heterogeneous nucleation on non-wetted surfaces. These ideas have been challenged by John Campbell [Yang, 2004, Campbell, 2003, Campbell, 2006] and others, who propose a nucleation-free mechanism for pore formation based on the concept of double oxide films or bifilms. In this scenario, during pouring in a casting process, the liquid surface of the alloy can fold upon itself. Because the liquid surface is covered by an oxide film, the folding action leads to bifilms, which are entrained into the bulk melt as a pocket of air enclosed by the bifilm. In effect, the bifilm with its air pocket is the beginning of a pore. After entrainment, the turbulence causes the bifilm to convolute and contract. Posterior pore growth can occur by the simple action of unfurling of the bifilms which in turn can be caused by mechanical action of the surrounding melt and by the aid of hydrogen diffusion into the pore.

It is interesting to note that if the bifilm theory is correct, then it follows that Eq. (5b) is irrelevant because there is no direct contact between gas and liquid and, hence, no surface tension is involved. However, the unfurling of bifilms is probably affected by the diffusion of hydrogen into the bifilm through the oxide layer. Consequently, a threshold amount of hydrogen in the liquid may be necessary to produce sufficient unfurling.

In this work, we keep (5b) as a criterion for pore origination and test the modeling results thus obtained against experimental data. When conditions (5) are met, we assume that a concentration, $n$, of spherical pores form with a known average initial radius, $r_0$. If the pores are in a supersaturated environment, they will grow by hydrogen diffusion. Assuming that the pores maintain the spherical shape during growth in the liquid, the rate of hydrogen mass, $m^H$, entering the pore by diffusion from the liquid is given by:

$$\frac{dm^H}{dt} = 4\pi r_P^2 \rho_l D_H \left.\frac{\partial C_l^H}{\partial r}\right|_{r=r_P} \tag{6}$$

where $r_P$ is the pore radius, $r$ is the radial coordinate measured from the center of the pore, and $D_H$ is the diffusivity of hydrogen in the liquid. We assume that the hydrogen gas inside the pore behaves as an ideal gas and that the partial pressure of other gases in the pore is negligible compared to that of hydrogen (this is reasonable in Al alloys given the high diffusivity of H compared to other gases). In this case, the rate of increase of the volume of the pore, $v_p$, can be calculated as:

$$\frac{dV_P}{dt} = \frac{R_H T}{p_S} \frac{dm^H}{dt} \tag{7}$$

where $R_H$ is the hydrogen gas constant. The radius of the pore, $r_p$, is then obtained as:

$$r_P = \left( \frac{3}{4\pi} V_P \right)^{1/3} \tag{8}$$

To estimate the radial derivative in Equation (6), we follow Yin and Koster [Yin, 2000] and consider the thickness of the diffusion boundary layer around the pore:

$$\left. \frac{\partial C_l^H}{\partial r} \right|_{r=r_P} \cong \frac{C_l^H - C_P}{\delta} \quad ; \quad \delta = 4\sqrt{D_H t} \tag{9}$$

where $C_P$ is the solubility of hydrogen at the local pressure and temperature, given by Sievert's law [Flemings, 1974], and $t$ is the time measured since pore nucleation. We must keep in mind that the pore growth model exists at the microscopic scale; there are no actual pores that are part of the geometry of the macroscopic model (the radial direction has no meaning in the macroscopic model). The pore radius calculated in Equation (8) should be interpreted as the average radius of pores in a location ***x*** where there are ***n(x, t)*** pores per unit volume.

Equation (6) is valid for pores that grow in the liquid. For pores growing in the mushy zone, the diffusion flux is taken as an average for liquid and solid [Poirier, 2001] and the pore area is multiplied by a shape parameter, α, in order to account for the distortion of the pores as they impinge into dendrites, with:

$$\alpha = \frac{r_P S_V}{3} \tag{10}$$

where α is the pore shape parameter and $S_V$ is the specific area of the pore (ratio of pore area to pore volume). For spherical pores, α = 1, while α > 1 for pores distorted by dendrites.

The pores grow while there is liquid remaining around them and lock in size after complete solidification. The total fraction of porosity in the casting as a function of time can be calculated as:

$$f_P(t) = \frac{1}{V} \int_V n(\mathbf{x},t) V_P(\mathbf{x},t) d\mathbf{x} \tag{11}$$

where $V$ is the volume of the casting.

To close the model, we need to provide some mechanism by which the concentration of dissolved hydrogen in the bulk liquid around the pore decreases to compensate the hydrogen provided to the pore (otherwise the pore will continue to grow indefinitely). That is, the transport equation for hydrogen needs to be modified to include a sink term. In the liquid, this equation is:

$$\frac{\partial C_l^H}{\partial t} = D_H \nabla^2 C_l^H - \mathbf{u} \cdot \nabla C_l^H - n C_l^H \frac{dV_P}{dt} \tag{12}$$

where the last term in the right-hand side represents the amount of hydrogen entering the pores from the liquid by diffusion. Because MULTIA is a two-phase code (liquid and solid), the gas phase is not included in the transport equations. Therefore, the validity of the proposed model needs to be restricted to small volume fraction of porosity, which is reasonable for the usual level of hydrogen microporosity measured in Al castings (< 1%). In this case, we can assume that the presence of the pores does not considerably affect the transport of other quantities like energy and momentum.

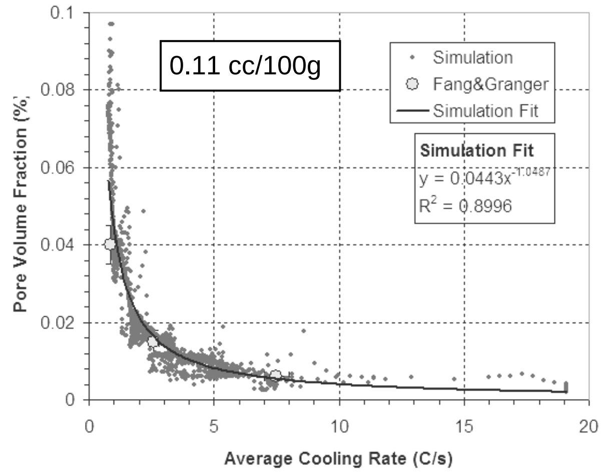
## Model Application and Discussion

The solidification model is discretized in space and integrated in time using a finite-element algorithm that is described by Felicelli *et al.* [Fang, 1989, Felicelli, 1998]. Al A356 alloy is solidified by simulation in a bottom-cooled, two-dimensional mold. The two-dimensional simulated casting has dimensions of 26 mm in width and 300 mm in height. Gravity acts downwards. In addition to the alloy solutes in A356 (Si and Mg), the gas-forming element, H, is considered. The computational domain is the casting; the top boundary is left open in order to allow for liquid flow to feed shrinkage. A no-slip condition is used for velocity at the bottom and two vertical boundaries, a stress-free condition is used on the top open boundary, and solute diffusion flux is set to zero on all closed boundaries. The thermal boundary conditions utilized in Poirier *et al* [Poirier, 2001] are used here, which are extracted from a measured thermal history in the plates cast by Fang and Granger [Fang, 1989]. The simulations start with an all-liquid alloy of the nominal composition initially at a uniform temperature of 958 K, which is 70 K of superheat. The thermodynamic and transport properties of the alloy, including the alloy elements and hydrogen, are the same as the ones in [Poirier, 2001], with the exception of the partition coefficient of hydrogen, for which we used the developments of Poirier and Sung [Poirier, 2002] to include the effect of the high eutectic fraction in A356.

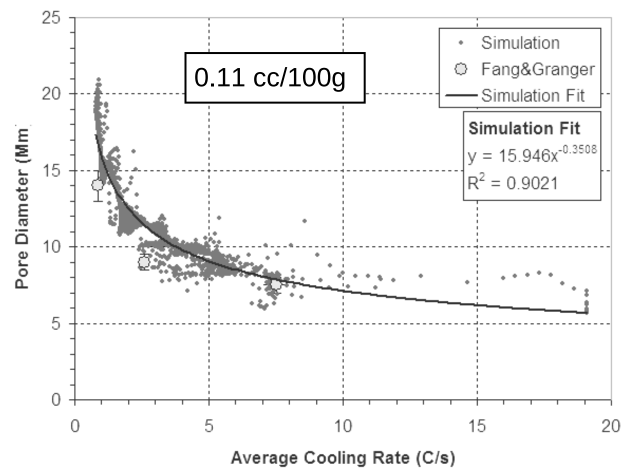
We performed simulations for the following values of initial hydrogen content: 0.11, 0.25, and 0.31 cc/100g (Note: 1 wt% = 1.12 x $10^4$ cc/100g), for which measured volume fraction of porosity and pore diameters were reported in the experiments by Fang and Granger [Fang, 1989]. In their work, these represented three different castings with the same geometry.

For all the calculations presented in this work, we used an initial pore diameter of 3 μm and a density of inclusions of $2x10^{11}$ $m^{-3}$. Taking the density of alumina as 4000 $kg/m^3$ and spherical inclusions of size equal to the initial pore size, this inclusion density corresponds to a concentration of approximately 5 ppm. This selection was guided by the work of Simensen and Berg [Simensen, 1980], who found that the smallest alumina particles in Al and Al-alloys ranged from 0.2 to 10 μm, while the concentration of oxides varied between 6 and 16 ppm.

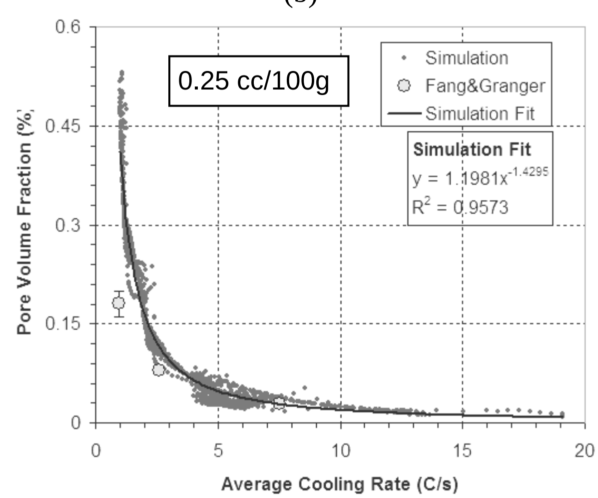
Figure 1 shows the variation of pore volume fraction and pore diameter vs. cooling rate in the solidified casting for all three values of initial hydrogen content. In this figure, the light-grey dots are calculated values that span all the casting; each dot represents the pore volume fraction or pore diameter calculated at a mesh node in the casting.



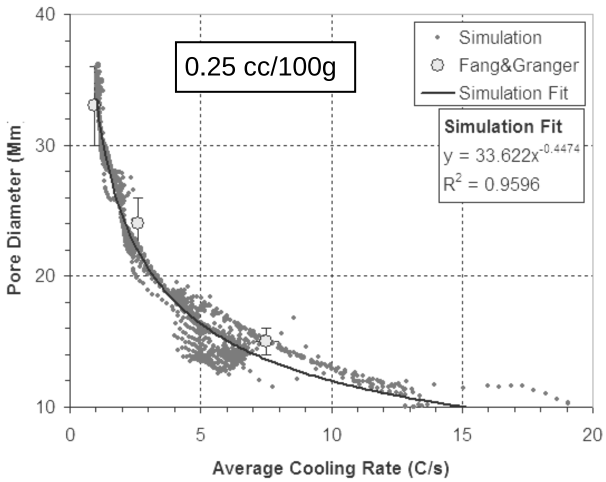

(a)



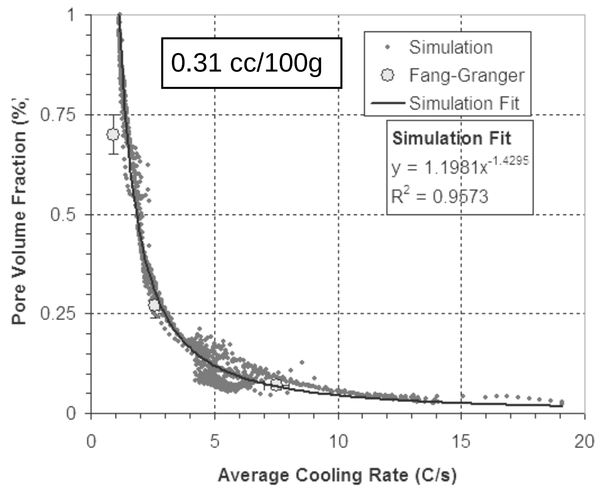

(b)



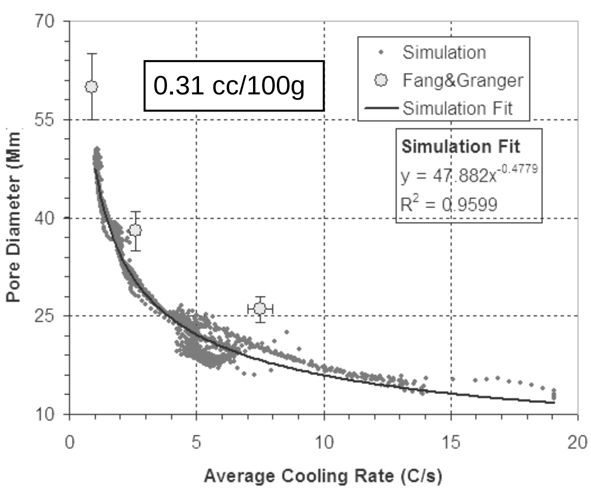

(c)




(d)




(e)




(f)

**Figure 1.** Pore volume fraction and pore diameter vs. cooling rate for different H contents.

A least-square fit of the calculated values is also shown as a solid black line. The experimental data of Fang and Granger [Fang, 1989] are indicated as larger light-grey dots; these were taken by manual reading from their paper, so bars estimating possible reading error are added. The experimental, larger, light-grey dots represent average values measured at a certain section of the casting, while the simulation shows the space variation within the entire casting. Certainly, the pore volume fraction and diameter are affected by other solidification variables in addition to cooling rate, but an average trend can be identified which is that they both decrease for higher cooling rates.

The quantitative agreement of simulated results with the experimental data is reasonable, considering that we are using a relatively simple, two-dimensional continuum model. As previously mentioned, all the results in Figure 1 were obtained using the same values of the initial pore diameter ($d_0$ = 3 μm) and concentration of inclusions ($n$ = 2x$10^{11}$ $m^{-3}$). Although the selected values fall in the experimentally measured range reported in [Simensen, 1980], it is possible that pores originate with a range of sizes and that the concentration of inclusions may differ from one casting to another in the experiments of Fang and Granger [Fang, 1989]. A closer agreement with the experimental data can be obtained if the parameters $d_0$ and $n$ are individually adjusted for each level of hydrogen content, but this approach was not pursued. In this sense, it is interesting to note that a same set of parameters works rather well for all three castings.

In addition to $d_0$ and $n$, a pore-shape parameter $\alpha$ = 1 was used to obtain the results for the castings with 0.25 and 0.31 cc/100g of hydrogen content, indicating that the growth of pores in these castings was apparently not significantly affected by impingement of the pores on dendrites. However, we needed to use $\alpha$ = 4 to reproduce the results of the 0.11 cc/100g casting, probably indicating that, in this casting, the pores were significantly distorted during growth. This observation is supported by the calculated fraction of liquid at which pores activate in each casting: 0.45, 0.75 and 0.85, for the 0.11, 0.25 and 0.31 cc/100g castings, respectively. We observed in the simulations that, once activated, pores grew very fast, indicating that in the 0.25 and 0.31 cc/100g castings, the pores developed most of their size at high fraction of liquid and were not significantly affected by dendrite impingement. In contrast, in the 0.11 cc/100g casting, pores started to grow at an already high fraction of solid and were most probably largely distorted by dendrites during growth.

## Conclusions

A continuum solidification model was extended to calculate the volume fraction of porosity and the pore-size distribution during solidification of Al alloys. The formation and growth of individual pores are calculated with a new hydrogen-diffusion technique in which the inclusions are treated as an additional alloy solute and subject to transport equations in the liquid and mushy zone. The method requires two parameters, the initial pore size and the concentration of inclusions, which are of physical nature and can be linked to measured data. The simulations show that the same set of these parameters is able to reproduce with reasonable agreement experimental data of different castings with varying levels of hydrogen content. A limitation of the method occurs when pores grow at high fraction of solid, which happens for the lowest level of hydrogen content. In this case, the growth of pores is highly affected by impingement on dendrites. Although the experimental data can still be reproduced through the use of a pore shape factor, a micro-model that links the pore shape parameter to physical quantities in the mushy zone would be desirable.

## Acknowledgements

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## Appendix - Oxide Bifilms in Mg Castings (by Prof. W. Griffiths)

Double oxide film defects in castings occur when the oxidized surface of the liquid metal is folded over onto itself and recombined into the bulk liquid. The characteristic of a double oxide defect in Al and Mg alloys is, therefore, that of a thin layer of gas separating unbonded oxide surfaces—an ideal site for initiation of failure of the microstructure under load [Campbell, 1991]. There is much evidence for their occurrence in Al castings, and recent investigations into the casting of pure Mg have demonstrated the presence of double oxide films in this alloy also, where their unbonded nature has been demonstrated by SEM examination [Griffiths, 2007]. Al-alloys casting manufacture has been governed by process design principles involving a minimum ingate velocity of $<0.5\ ms^{-1}$. This has been shown experimentally to be valid in the case of Mg alloys also [Lai, 2004]. Double oxide film defects in Al have been shown to be nucleation sites for hydrogen (H) porosity [Raeiszadeh, 2006], and it is to be expected that gas porosity can be nucleated more easily in this way in Mg alloys, because a MgO film is porous and should allow diffusion of H gas, whereas alumina forms a protective film. Double oxide film defects in Mg have also been shown to be ideal sites for the nucleation of shrinkage porosity [Griffiths, 2007, Lai, 2004].

While the role of oxide film defects in Al alloys has been the subject of much research, their role in Mg alloys is still to be investigated. However, it is to be expected that they have similar, deleterious effects on properties due to the similar nature of the two alloy classes.

## Presentations/Publications/Patents

1. S.D. Felicelli, E. Escobar de Obaldia and C.M. Pita, “Simulation of hydrogen porosity during solidification,” *American Foundry Society Transactions*, vol. 115, paper 07-078, pp. 1-13 (2007) – BEST PAPER AWARD.
2. S.D. Felicelli, C. Pita and E. Escobar de Obaldia, “Modeling the onset and evolution of hydrogen pores during solidification,” *Shape Casting: The 2nd International Symposium*, edited by P. Crepeau, M. Tiryakioglu and J. Campbell, TMS (The Minerals, Metals & Materials Society), ISBN: 978-0-87339-660-8, 2007, pp. 201-208.

## References


1. [Campbell, 1991] "Castings", J. Campbell, Butter-worth-Heinemann, London, 1991.
2. [Campbell, 2003] Campbell J: Castings 2nd Edition – The New Metallurgy of Cast Metals. Butterworth-Heinemann, Oxford, UK, 2003.
3. [Campbell, 2006] Campbell J: Entrainment Defects, Materials Science and Technology Vol. 22, n 2, (2006), pp 127-145.
4. [Carlson, 2003] Carlson K D, Zhiping L, Hardin R A and Beckermann C: Modeling of porosity formation and feeding flow in steel casting *Modeling of Casting, Welding and Advanced Solidification Processes X*, D.M. Stefanescu, J. Warren, M. Jolly, and M. Krane (Eds.), The Minerals, Metals, & Materials Society, 2003, 295-302.
5. [Fang, 1989] Fang Q T and Granger D A: Porosity formation in modified and unmodified A356 alloy castings, *AFS Trans.* Vol. 97 (1989), 989-1000.
6. [Felicelli, 1998] Felicelli S D, Heinrich J C and Poirier D R: Finite element analysis of directional solidification of multicomponent alloys, Int. *J. Numer. Meth. Fluids* Vol. 27 (1998), 207-227.
7. [Felicelli, 2000] Felicelli S D, Poirier D R and Sung P K: A model for prediction of pressure and redistribution of gas-forming elements in multicomponent casting alloys, *Metall. Mater. Trans. B* Vol. 31B (2000), 1283-1292.
8. [Flemings, 1974] Flemings M C: *Solidification Processing* (New York: McGraw-Hill), pp 203-210.
9. [Griffiths, 2007] W. D. Griffiths and N.-W. Lai, *Met. and Mat. Trans. A*, Jan. 2007, vol. 38A, 190-196.
10. [Guo, 2003] Guo J and Samonds M T: Microporosity simulations in multicomponent alloy castings, *Modeling of Casting, Welding and Advanced Solidification Processes X*, D.M. Stefanescu, J. Warren, M. Jolly, and M. Krane (Eds.), The Minerals, Metals, & Materials Society, 2003, 303-311.
11. [Han, 2002] Han Q and Viswanathan S: Hydrogen evolution during directional solidifications and its effect on porosity formation in aluminum alloys, *Metall. Mater. Trans. A* Vol. 33A (2002), 2067-2072.
12. [Lai, 2004] N.-W. Lai, PhD Thesis, University of Birmingham, UK, 2004.
13. [Lee, 2001]Lee P D and Hunt J D: Hydrogen porosity in directional solidified aluminum-copper alloys: a mathematical model, *Acta Mater.* Vol. 49 (2001), 1383-1398.
14. [Lee, 2004] Lee P D, Chirazi A, Atwood R C and Wang W: Multiscale modeling of solidification microstructures, including microsegregation and microporosity, in an Al-Si-Cu alloy, *Mater. Sci. Eng. A* Vol. A365 (2004), 57-65.
15. [M'Hamdi, 2003] M'Hamdi M, Magnusson T, Pequet Ch, Amberg L and Rappaz M: Modeling of micropososity formation during directional solidification of an Al-7%Si alloy, *Modeling of Casting, Welding and Advanced Solidification Processes X*, D.M. Stefanescu, J. Warren, M. Jolly, and M. Krane (Eds.), The Minerals, Metals, & Materials Society, 2003, 311-318.
16. [Major, 1997] Major J F: Porosity control and fatigue behavior in A356T61 aluminum alloy, *AFS Trans.* Vol. 105 (1997), 901-906.
17. [Poirier, 2001] Poirier D R, Sung P K and Felicelli S D: A continuum model of microporosity in an aluminum casting alloy, *AFS Trans.* Vol. 109 (2001), 379-395.
18. [Poirier, 2002] Poirier D R and Sung P K: Thermodynamics of hydrogen in Al-Si alloys, *Met. Mater. Trans. A* Vol. 33A (2002), 3874-3876.
19. [Raeiszadeh, 2006] R. Raeiszadeh and W. D. Griffiths, *Met. Mat. Trans. B*, Dec. 2006, vol. 37, 865-871).
20. [Sabau, 2002] Sabau A S and Viswanathan S: Microporosity prediction in aluminum alloy castings, *Metall. Mat. Trans. B* Vol. 33B (2002), 243-255.
21. [Simensen, 1980] Simensen C J and Berg G, A survey of inclusions in aluminum, *Aluminium*, Vol. 56, No. 5, pp. 335-340.
22. [Stefanescu, 2005] Stefanescu D M: Computer simulation of shrinkage related defects in metal castings – a review. *Int. J. Cast Met. Res.* Vol. 18 (2005), 129-143.
23. [Sung, 2002] Sung, P K, Poirier D R and Felicelli S D: Continuum model for predicting microporosity in steel castings, *Modelling Simul. Mater. Sci. Eng.* Vol. 10 (2002), 551-568.

24. [Yang, 2004] Yang X, Huang X, Dai X, Campbell J and Tatler J: Numerical modeling of entrainment of oxide film defects in filling of aluminium alloy castings, Int. *J. Cast Met. Res* Vol. 17 (2004), 321-331.
25. [Yin, 2000] Yin H. and Koster J., “In-situ observed pore formation during solidification of aluminium”, *ISIJ International*, vol. 40(4), pp. 364-372.
26. [Zhu, 2005] Zhu J D, Cockcroft S L, Maijer D M and Ding R: Simulation of microporosity in A356 aluminium alloy castings, *Int. J. Cast Met. Res.* Vol. 18 (2005), 229-235.