3. AUTOMOTIVE METALS—CAST

A. Improved Automotive Suspension Components Cast with B206 Alloy

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Contractor: United States Automotive Materials Partnership (USAMP)
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Objective

- The objective of this program 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 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 solution and aging time and temperatures which produce desirable strength with 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 CAE and design information and establish the feasibility of using cast B206 alloy components to replaced forged aluminum parts.

Accomplishments

- The project was officially initiated October, 2005.
- Mr. Richard Osborne accepted project leadership responsibilities in November 2008 after Mr. Eric McCarty left Chrysler LLC. Efforts are on-going for the project to hire a new independent technical consultant (ITC) to assist in completing the project by December 31, 2009.
- Phases 1, 2, and 3 have been completed.

- Phase 4 is on-going with semi-permanent mold and ablation castings delivered the third quarter of 2008. Ballard Brass & Aluminum, Inc. produced semi-permanent mold castings, an economically favorable process that is typically used for the 206 alloy. Eck Industries/Alotech produced castings using the ablation process, a direct-chill process that is well suited to the B206 which responds better to fast solidification rates. Castings were delivered with optimum T4 and T7 chemistries and heat-treatment conditions. Comprehensive mechanical testing is planned for the second quarter of 2009.

PHASE 1:

Phase 1 is complete and consists 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 solidification 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 %):

T4 Temper

The alloy contains 4.7 to 4.9% Cu, 0.35 % Mg, and 0.2 % Mn. The expected tensile properties are (Yield Strength [YS], ultimate tensile strength [UTS], elongation): 250–260 MPa, 430–450 MPa, and 18 to 22%.

T7 Temper

For a ductile T7 version, the alloy contains 4.2 to 4.4% Cu, 0.15% Mg, 0.2% Mn, 0.10% Fe, 0.10% Si. The expected average tensile properties would be (YS, UTS, elongation): 370–390 MPa, 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 one 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 and 225°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

Phase 3 has been completed. A cost model was developed by A. Edmund. P. E. Herman, 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

Phase 4 is in progress. The intent of Phase 4 was to produce and test B206 castings using green sand 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. 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 semi-solid 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 Dr. Tiryakioğlu and Prof. John Campbell were adopted by Nemak, and the 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, el = 10%). Based on Phase 1 results, the project team concluded that the slow solidification rate in the full sand mold was the primary reason why the castings did not achieve the desired properties.

To increase the solidification rate, Nemak machined an aluminum drag, poured 30 castings and heat treated 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.

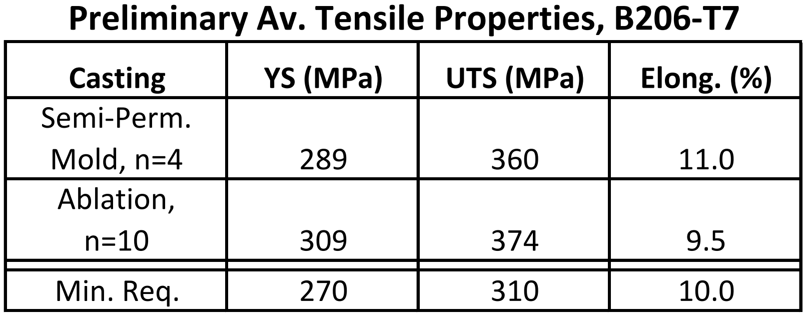
Ballard Brass & Aluminum, Inc.

Ballard was selected to produce 50 castings using an optimized semi-permanent mold process. Castings have been produced using both T4/T7 chemistry and each group heat treated to the T4/T7 condition, respectively. Finished castings have been delivered to Chrysler and are being inspected and processed for material property testing.

Eck Industries/Alotech

Eck Industries and Alotech produced 50 castings, 25 of the T4 temper and 25 of the T7 temper, with the ablation casting process, which generates high cooling rates and low levels of porosity. Castings were poured and delivered in July 2008 using the same T4 and T7 chemistries and heat-treat schedules as the semi-permanent mold castings. Preliminary tensile results from specimens excised from castings heat treated to the T7 condition are promising and shown in Table 1.

Table 1. Preliminary tensile results for samples excised from semi-permanent mold and ablation castings in the T7 heat treatment condition



Preliminary Av. Tensile Properties, B206-T7

Casting	YS (MPa)	UTS (MPa)	Elong. (%)
Semi-Perm. Mold, n=4	289	360	11.0
Ablation, n=10	309	374	9.5
Min. Req.	270	310	10.0

Component Testing

- Semi-permanent mold and ablation castings are being delivered to both General Motors and Westmoreland Mechanical Testing and Research. General Motors will conduct bench durability testing in accordance with forged 6061-T6 control-arm components. Westmoreland will complete tensile, compression, fracture toughness and corrosion testing from samples excised from both processes and heat treatment tempers.
- In addition to component and material testing, a select group of cast control arms will be subjected to load-deformation failure testing to determine whether any casting structural defects exist and can be avoided with better melt quality and improved mold filling system design. A full project report will be available in December 2009.

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, semi-permanent mold and ablation are expected to meet the target mechanical properties. The project will be completed in December 2009.

Aluminum B206 Cast Component Rationale

The 206 alloy is significantly stronger than the 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, however, 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 AMD305—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 AMD305 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 aluminum components, and the low-cycle fatigue life of B206 alloy is ten times that of A356 alloy castings for an equivalent stress level. AMD305 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 proposed in this project will examine 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 be 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 CO_2 emissions and improve fuel economy through increased CAFE 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 aluminum castings.

Program and Deliverables

This project was initially planned to be completed in 30 months and proceeded 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 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 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 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, control arm 'Mule' castings will be manufactured by the composite precision sand casting process at Nemak. Semi-solid cast parts will also be made at Mercury Castings.

In AMD305 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, which 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, YS in MPa, and elongation) that one may expect as the composition is varied between the upper and lower limits for this alloy in the Aluminum Association 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.

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 in.). The tensile properties obtained from these castings are shown Figure 4, together with data published for the more commonly used aluminum casting alloys.

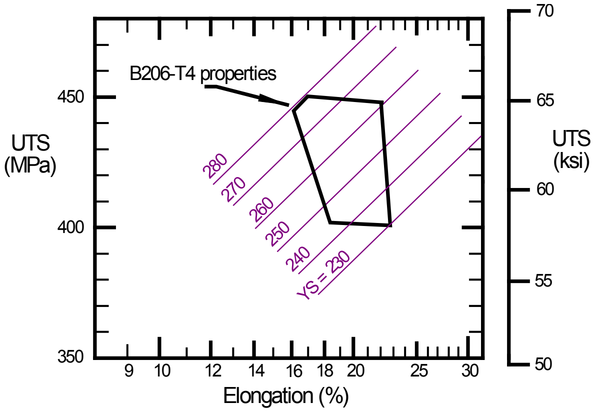


Figure 2. B206-T4 tensile properties.

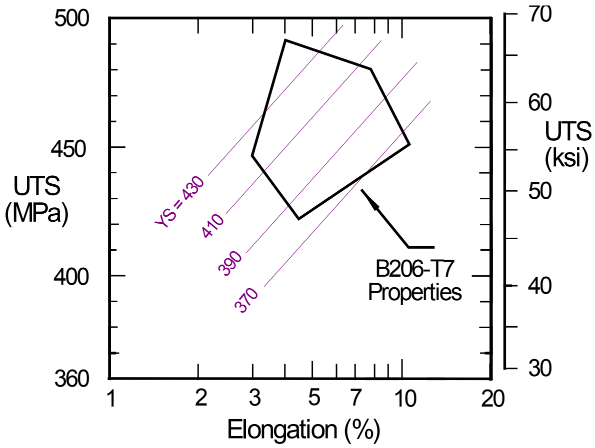


Figure 3. B206-T7 tensile properties.

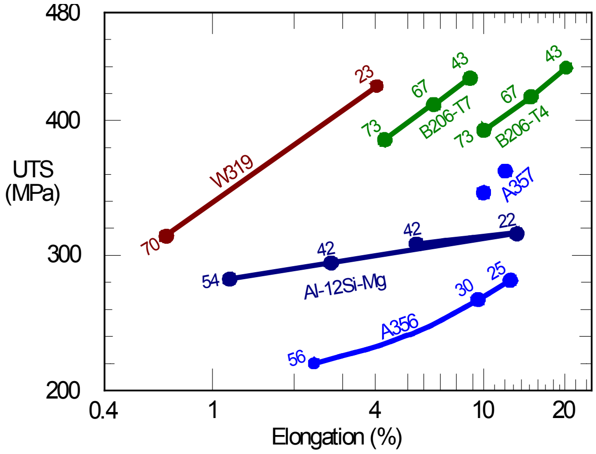


Figure 4. Range of mechanical properties in five aluminum casting alloys.

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 are 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 ASTM specification G110 was used. This procedure correlated well with the results of a standard alternate immersion test in 201 alloy,[*] 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 ‘in between’ the safe areas, at aging temperatures between 100 and 180°C.

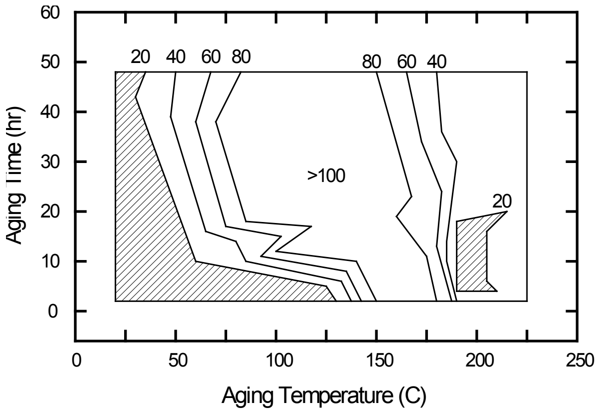


Figure 5. Average Depth of Corrosion.

In Phase 2 of our program, immersion stress-corrosion tests were conducted in accordance with ASTM G47-98 standard. Specimens were all naturally aged for 3 days and artificially aged for different durations at temperatures between 100 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 and 175°C, which is consistent with intergranular corrosion results outlined in

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

Figure 6. More analysis will be conducted for possible correlation between the results from the two test methods.

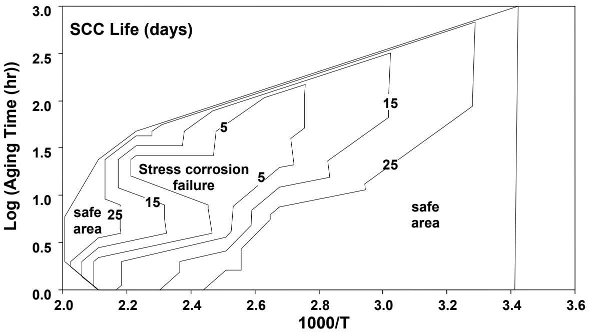
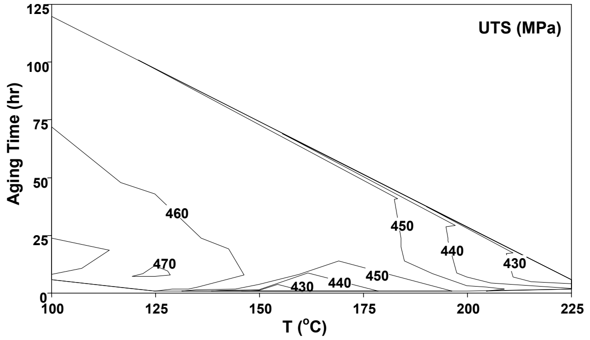
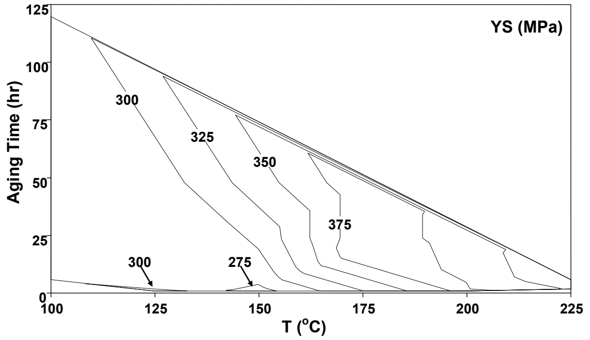


Figure 6. Stress-corrosion cracking life contours as a function of artificial aging time and temperature.

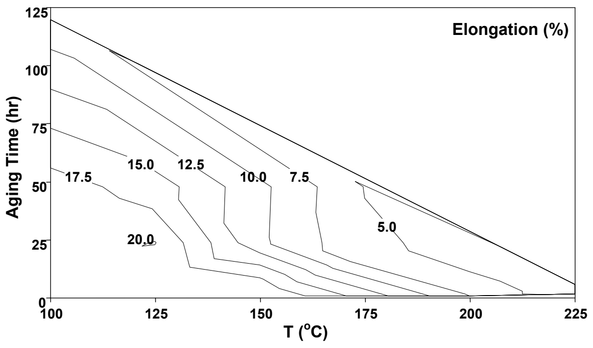
Contour plots of tensile properties after artificial aging at temperatures between 100 and 225°C for various durations are presented in Figure 7. Highest UTS and elongation are obtained at an artificial aging for 12–24 hours at 125°C. A small set of experiments are planned at Alcan Laboratories to obtain more detailed results.



(a)



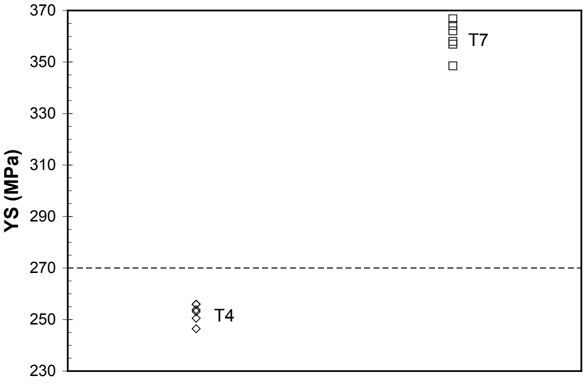
(b)



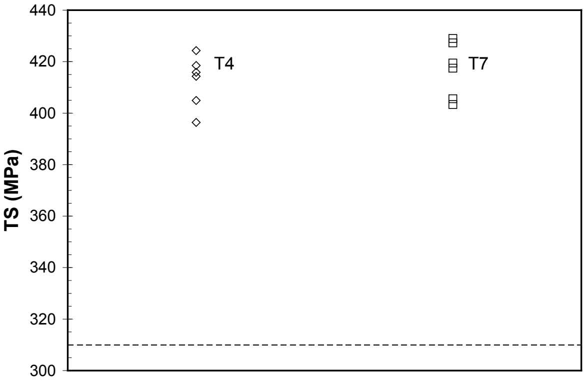
(c)

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

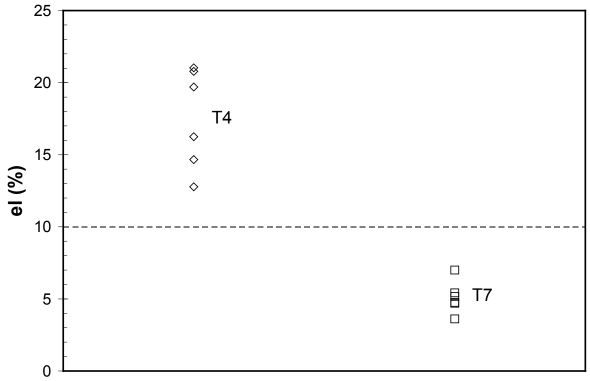
Two castings produced by the semi-permanent mold process (with an aluminum drag) at Nemak were tested by excising tensile coupons from three locations in each casting. The tensile properties are summarized in Figure 8. The desired level of each property is indicated by a dashed line.



(a)



(b)



(c)

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

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:

1. G. K. Sigworth and 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).
2. J. F. Major and G. K. Sigworth, "Chemistry/Property Relationships in AA 206 Alloys," paper 06-029, AFS Transactions (presented at 2006 AFS Congress).

B. Magnesium Powertrain Cast Components (AMD304[*])

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

Objective

- Demonstrate and enhance the feasibility and benefits of using magnesium alloys in place of aluminum 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, 28%.

Approach

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

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[*] Denotes project 304 of the Automotive Materials Division of the United States Automotive Materials Partnership, one of the formal consortia of the United States Council for Automotive Research set up by Chrysler, Ford, and General Motors to conduct joint, precompetitive research and development (see www.uscar.org).

- Refine the engine component designs as necessary (updating to match the properties of the alloy selected for each component), design and build tools and patterns, and cast the engine components. (Task 4)
- Excise specimens from the cast components and develop a full mechanical and corrosion design database for the alloys. Create an original equipment manufacturer (OEM)—common material specification for magnesium powertrain alloys. (Task 5)
- Assemble complete engines, dynamometer-test the components, and conduct end-of-test teardowns. Refine the cost model to support determining the cost-effective performance of the engine. (Task 6)

Accomplishments

- In the fiscal years (FYs) 2001 to 2007, Tasks 1 through 4 were completed. At the Phase II gate review it was announced that the achieved mass reduction for the magnesium components was 28 percent, nearly twice that of the original target. Alloys were selected for each magnesium engine component; component designs were revised accordingly; casting tooling was designed and built; and all four magnesium components were cast, machined, and delivered for component and engine testing. The five basic research projects in support of the objectives of Task 3 were also completed.

FY 2008 Accomplishments:

- Passed pulsator testing of the head gasket which had been designed by Dana Victor Reinz Corp. specifically for the requirements of the MPCC magnesium cylinder block and aluminum cylinder heads. The head gaskets and the rest of the bill of materials for engine assembly were delivered to Roush Industries and several test engines were assembled.
- Completed and passed bench-top Thermtronic testing of the cylinder block: thermal cycling and thermal soak.
- Completed calibration of the engine dynamometer and demonstrated with the successful operation of an aluminum production Duratec engine. Passing this test was an essential requirement for starting magnesium engine testing.
- Completed and passed the Hot Scuff Engine Test, which is a measure of piston/ring/bore design compatibility as well as the adhesion and durability of the thermal sprayed, wear-resistant coating that was applied to the cylinder bores in lieu of cast-in-place or pressed-in-place liners.
- Completed and passed the Cold Scuff Engine Test, which is a much more severe test of the bore coating adhesion and wear resistance. It a very critical and difficult test to pass. Hot and Cold Scuff Engine Tests are gateway tests to engine durability testing.
- Initiated the Deep Thermal Shock Engine Test. However, during break-in operation of the engine, bulkhead numbers 2 and 3 broke and cracks were detected propagating across the remaining bulkheads (1 and 4). Testing was stopped and root cause analysis was conducted. The apparent cause of failure was identified and finite element analysis was initiated to demonstrate the ability to predict the failure.
- Completed High Speed Durability Engine Test of an aluminum block with magnesium oil pan and front cover and demonstrated durability of these two components.
- Completed a Coolant Corrosion Engine Test of the complete MPCC magnesium-intensive engine. Run at low load to protect the bulkheads, this 672-hour test (based on a Ford industry standard) provides a good measure of the effectiveness of the Honeywell coolant, which contained an additive to protect the magnesium. Analysis of the coolant samples and teardown analysis of the engine are ongoing.
- Completed tensile testing of specimens excised from each of the four cast components (cylinder block, oil pan, front engine cover, and rear seal carrier). The results compared favorably with the results of the cast specimens tested in Phase 1 of the Project. The results were placed in the Lightweighting Materials electronic database.
- Completed cost analysis of the magnesium-intensive engine. This involved putting manufacturing and economic data into the cost model for each magnesium part (cylinder block, oil pan, and front engine cover). This yielded the cost per pound (or kg) saved and the identification of the major cost contributors. In general, the mass reduction was cost effective, relative to the cost of gasoline; $3.89 per pound of mass reduced vs a

current gasoline price of nearly $4.00 per gallon. The original target of $2.00 per pound mass reduced was not achieved, primarily due to increases in the cost of magnesium ingot from approximately $1.30 to $1.92 per pound between 2003 and 2008.

- The patent application for the structural details of the magnesium cylinder block was accepted and US Patent No. 7,284,528 was issued on October 23, 2007. The rights of the patent were assigned to USAMP.

Future Direction

- Complete the FEA analysis of the bulkhead failures in the Deep Thermal Shock Engine Test.
- Complete teardown and analysis of the Coolant Corrosion engine.
- Complete the final report for the Magnesium Powertrain Cast Components Project by March 31, 2009.

Introduction

The MPCC project team's vision is of a magnesium-intensive engine that is cost-effective, lightweight, and meets the manufacturability and durability requirements of the automotive industry. The approach taken was the redesign of an aluminum production engine (2.5L Ford Duratec) to a magnesium-intensive version; that is, to convert the cylinder block, bedplate, oil pan, and front engine cover to magnesium. All other parts of the engine were production carryover. The design, materials testing, tooling design, and casting of the parts were accomplished in prior years. Summaries can be found in previous progress reports. In 2008 component and engine testing was completed and is summarized in this, the FY 2008 Progress Report. The original aluminum block and MPCC magnesium blocks are shown in Figures 1 and 2, respectively. An assembled MPCC engine with its magnesium front cover and oil pan are shown in Figure 3.

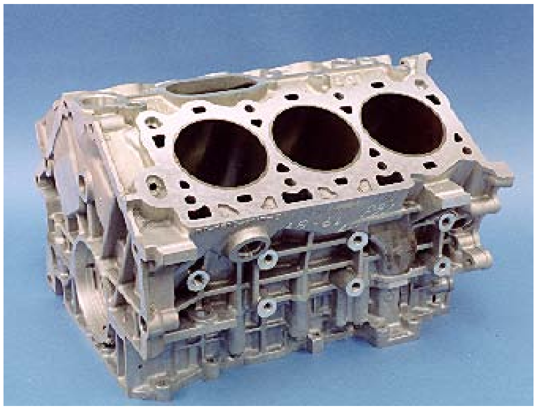

Figure 1. Aluminum production V6 cylinder block and bedplate.

Figure 2. MPCC magnesium cylinder block.

Figure 3. MPCC magnesium-intensive engine with valve covers removed.

Though initially intended to contain a magnesium bedplate, the final design became that of a deep skirt block without a bedplate, which necessitated also adding a magnesium rear seal carrier to the design.

All component testing and Hot Scuff and Cold Scuff engine dynamometer testing was completed in 2008. However, the original engine durability test plan was changed because of a bulkhead failure that occurred in the first of the durability tests. Root cause analysis of the failed block was completed. Based on the results, the MPCC team revised the engine test program and two durability tests were completed; a 675-hour High Speed Durability test of the magnesium front cover and oil pan, which were mounted on the aluminum cylinder block and a 672-hour Coolant Corrosion test, which was run at low load to protect the bulkheads. A summary of the results of the completed component and engine testing is provided. Tensile test results for specimens excised from the cast magnesium components are also presented. Finally, a summary of the cost model application is presented. The MPCC project team is completing the final report and will complete the project in early 2009.

Head Gasket Design and Pulsator Testing

Many parts for the magnesium-intensive engine were carry-over from the production aluminum Duratec. This was not possible for the head gaskets. Differences in material properties of magnesium relative to aluminum (modulus, yield strength, coefficient of thermal expansion) required a new design. The Dana Victor Reinz Corporation designed a 4-layer, selectively-coated 301 stainless steel gaskets, based on Dana's Wave-Stopper Technology. A schematic is shown in Figure 4.

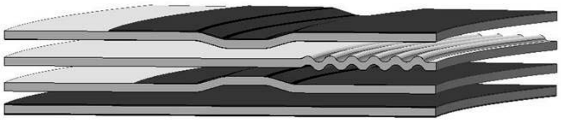

Figure 4. A schematic of the Dana Victor Reinz-MPCC head gasket cross section.

Sealing was assessed at 100% bolt load and 70% bolt load, the latter load case being done to anticipate the effect of possible bolt load loss due to magnesium creep and/or gasket relaxation. FEA predicted acceptable performance of the gasket, but pulsator testing was required to confirm this. Deep thermal shock testing was also done before releasing the gaskets for the magnesium-intensive engine. Testing was done on a magnesium block with an aluminum head and the test gasket between. Pulsator testing comprised 10,000,000 cycles to 70 bars. Thermal shock testing comprised subjecting the block to 278 cycles from –18 to 115^{o}C. The head gaskets passed both tests; e.g., there was no loss of coating, sealing stress transfer was as predicted, and there were no signs of leakage or Brinelling into the deck face of the cylinder block.

Cylinder Block Component Testing

The objective was to determine effects of thermal cycling and thermal soak on cylinder bore and crank bore distortion due to permanent growth of the magnesium alloy. The magnesium alloy used for the MPCC cylinder block is AMT-SC1, which requires heat treatment. Testing was required to determine if the high engine operating temperatures would further "heat treat" the alloy and cause permanent growth (expansion) of the cylinder block. We were also interested in critical fastener clamp load retention, specifically the head bolts and the bulkhead bolts. Detroit Testing Laboratory conducted the testing. A block configured for testing is shown in Figure 5.

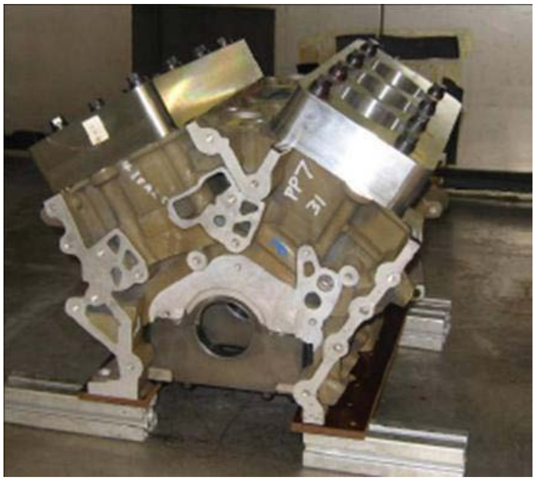

Figure 5. Magnesium block assembled for thermal testing.

Thermal Cycling

The block was cycled from -40^{o}C to 150^{o}C for 100 cycles. Cylindricity (bore out-of-roundness) increased slightly, but less than is typical of production aluminum blocks with iron liners. There was head bolt clamp load loss, but also within acceptable ranges.

100-Hour Thermal Soak

A second magnesium block was held for 100 hours at 150°C. Initial measurements suggest no growth, but the complete set of measurements is in progress.

Engine Testing—Hot and Cold Scuff

The MPCC magnesium-intensive engine used thermal-sprayed cylinder bores in place of iron or aluminum liners. There were several reasons for this: avoidance of the extra mass of the liner, minimizing bore distortion (cylindricity) by strengthening and stiffening the bore walls, and simplifying head gasket design. This significant change to the magnesium engine required that scuff testing be done to determine the fit and compatibility of the pistons and rings with the new bore, and to ensure that bore wear and coating adhesion were acceptable. Scuff testing was conducted at Roush Industries on fully assembled magnesium-intensive engines.

Hot Scuff Engine Test

This test consisted of running the Ford test protocol, high engine rpm for thirty minutes. Subsequently the engine was disassembled and the bores, pistons, and rings inspected for wear. Inspection confirmed normal wear of the bore coating and normal wear of the piston skirt (see Figure 6).

Figure 6. Post-hot scuff tested piston showing acceptable wear of the piston skirt coating.

Cold Scuff Engine Test

This test required 120 cycles of sub-zero cold starts at light load and low engine speed. It simulates low lubrication conditions because the oil has drained from the bore surface and is cold enough to take time to recoat the surface. This is generally a very demanding test and failure would be an indicator of future problems on the engine durability tests planned for the magnesium-intensive engines.

Both the pistons and bores looked excellent at the end of test. There was no scuffing of the rings or pistons, or in the bores. A ring tip scratch occurred in one bore, but this was not indicative of scuff, and is not unusual in engine testing. A typical bore after cold scuff testing is shown in Figure 7.

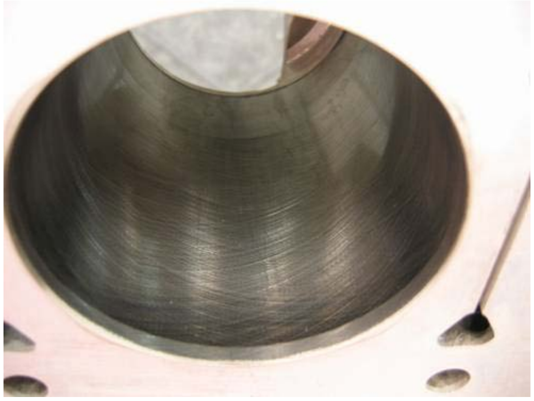

Figure 7. Cylinder bore at end of cold scuff test. Honing marks are evident.

Deep Thermal Shock Test—Bulkhead Failure and Root Cause Analysis

The Deep Thermal Shock Test (DTS) was to have been the first of four durability tests for the magnesium-intensive engine. However, during break-in runs the behavior of the engine showed higher blow-by than the production engine and leakage past the crank seals and the oil fill cap. Subsequently, the engine oil pressure dropped and the engine began making bottom-end noises. Inspection revealed complete failure of the two interior bulkheads, numbers 2 and 3, and cracks propagated partially across bulkheads 1 and 4 (see Figure 8).

An intensive root cause analysis was launched by the MPCC project team. It included both failure analysis of the engine and a reevaluation of the FEA work done during engine design. Results point to the interface between the cast iron inserts and the magnesium bulkheads which were cast around them. FEA modeling is being done to include this possibility in the safety factor predictions. If confirmed, then preventing this failure mode should be possible in future engine designs.

Figure 8. Fracture of DTS engine bulkhead 3.

Anticipating the correctness of root cause analysis, the MPCC project team changed the engine durability test plan. Two engines durability tests were adopted and completed: a 675-hour High Speed Durability Test and a 672-hour Coolant Corrosion Test.

675-Hour High Speed Durability Test

Because the root cause analysis of the DTS engine test failure did not indicate a method to prevent bulkhead failure in the already-cast cylinder blocks, the magnesium front cover and oil pan were mounted on a production aluminum engine in place of the aluminum cover and pan. Then the intended High Speed Durability Test was run.

The 675-hour test consisted of 75 cycles through over 200 power/torque conditions and a 1-hour soak. Checks of all fasteners, including RIBE's Aluform aluminum fasteners which were used on the front cover and oil pan, were performed every nine hours. At the end of test, break-away toques for all bolts were measured and parts were inspected for signs of damage, including corrosion. Standard coolant (no protective additive) was used for this test.

The front cover bolts went the full 675 hours and showed no loosening during testing; neither the RIBE bolts nor the carry-over production bolts. The oil pan developed a small leak during testing, which was determined to be due to a casting defect, either a hot crack or hot tear. It was repaired with epoxy and the pan completed the test without further incident. No evidence of corrosion was seen on either the cover or the oil pan.

During the test, an assessment of the noise level of the engine was made. It was concluded that there was no evidence of unusual noise or vibration due to the magnesium parts. It was recommended that more systematic testing be done to quantify this promising result.

672-Hour Coolant Corrosion Test

An important objective of this project was to determine the corrosion behavior of the magnesium cylinder block in the presence of ethylene glycol water-based coolant. Extensive bench testing was done of all considered magnesium alloys in the earlier phase of the Project. After testing, the Honeywell experimental coolant was selected for the engine dynamometer coolant.

Because the intended durability testing could not be done, the team chose to do a different durability test which was based on the Ford BL 102-02 standard for screening coolant behavior. The major change to the test protocol was to run the engine at low load, low enough to protect the bulkheads but high enough to achieve the necessary coolant temperatures to effectively test the coolant/component interfaces. The engine was run at 2,000 rpm at 50 kN with periodic high and low temperature soaks.

Testing went well and no issues were reported. Coolant samples were drawn before and after the test and at 96-hour intervals. Analysis is ongoing and the results are promising.

Tensile Testing of Excised Specimens

In Phase 1 of the MPCC Project, an extensive mechanical and thermo-physical property database was created of the several die-casting and sand-casting magnesium alloys considered by the project team. Test specimens were cast to size. In Phase II, having cast the magnesium components for engine testing, specimens were excised from these components and tensile tested at room temperature and at 150°C. A comparison of these results with those of cast specimens will be helpful to design engineers using the database. This work has been completed. All mechanical testing was done at Westmoreland Mechanical Testing & Research. Figure 9 shows an example of locations from which specimens were excised from the structural oil pan. Specimens were excised from the sand-cast cylinder block, the high-pressure die-cast front cover, and the thixomolded rear seal carrier.

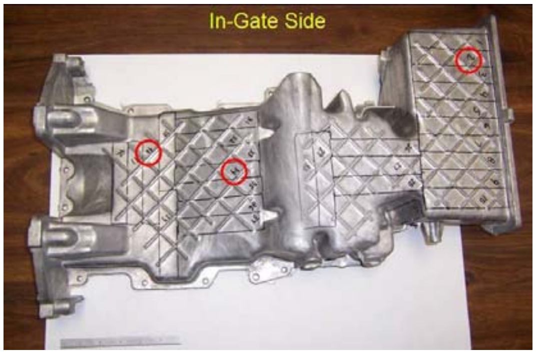

Figure 9. Structural oil pan showing locations of excised specimens.

Comparison of the tensile properties of the cast specimens and the excised specimens showed them to be in relatively close agreement, which suggested that it was possible to obtain good materials properties even in complex castings. Although, it should be noted that extensive effort was made by the team members to make good castings for component and engine testing. In addition, excised specimens were X-rayed and screened at ASTM E505 Level 1 quality at Chrysler.

The North American Die Casting Association (NADCA) invited the MPCC project team to include a summary of the tensile test results in the next edition of the NADCA Product Specification Standards for Die Castings. The data were provided and will be available to the public in 2009.

Determination of Cost-Effective Mass Reduction

A final criterion for a cost-effective, magnesium-intensive engine is that it indeed be cost effective. In Phase 1 of the MPCC Project, technical cost models were created for both the sand-cast and high-pressure die-cast magnesium components. In Phase 2 of the Project, we revisited the technical cost models, revised as necessary, and populated the models with “manufacturing” data collected during the casting trials and obtained calculated costs per unit of mass reduction and breakdowns of the various factors contributing to the overall cost of the components.

Figure 10 shows the calculated cost breakdown for the manufacturing costs of the structural oil pan. It compares the costs of the production aluminum pan with those of the magnesium pan. The terms “old” and “new” in the figure indicate the results of the Phase 1 and Phase 2 calculations, respectively. The Phase 2 calculations reflect the actual manufacturing data that were not available for Phase 1. It also reflects the recent “short term” increase in the cost of magnesium ingot.

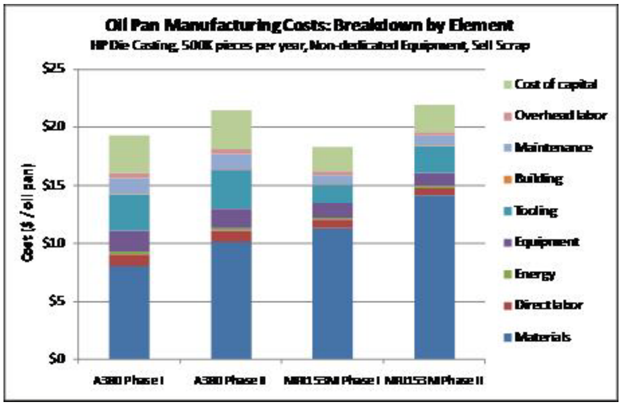

Figure 10. Cost elements in the manufacturing of the structural oil pan.

The overall results indicate that when the models were run using the current magnesium prices, the cost of 28% mass reduction for the engine with the components converted from aluminum to magnesium was less than $4 per pound, approximately that of the then-current price of gasoline in dollars per gallon. Most of the cost was attributable to the cost of the cylinder block. The costs of mass reduction of the oil pan and front engine cover were essentially zero. Nevertheless, the primary cost contributor for all of the magnesium components was the cost of magnesium ingot, which increased 50% between 2003 and 2008, from an estimated $1.30 to $1.92.

Conclusions

In 2008, we were able to physically test major magnesium engine components based on the excellent progress the MPCC project has made since its inception in 2001. The significant challenge for the Mg-intensive engine has been identified as designing around the thermal expansion coefficient of magnesium, which is greater than that of aluminum. This mismatch drove numerous final design attributes and probably contributed to the failure of the bulkheads in the Deep Thermal Shock engine test. If analysis confirms our hypothesis, it appears that the thermal expansion mismatch problem can in fact be avoided through redesign.

Our results indicate that cost, corrosion, and creep behavior do not appear to be showstoppers in the implementation of magnesium engine components. However, field performance and robustness have yet to be demonstrated.

Over the course of this project, our collaborations have yielded considerable valuable information about creep-resistant magnesium alloys, their castability, designing with them, and the cost factors entering into achieving cost-effective mass reduction.

Presentations/Publications/Patents

1. B. R. Powell, “Automotive Applications of Cast Magnesium,” presented to the American Foundry Society, Saginaw Valley Chapter Education Series, Saginaw, MI, February 13, 2008.
2. B. R. Powell, W. L. Miller, L. J. Ouimet, J. A. Hines, J. E. Allison, R. S. Beals, and P. P. Ried, “Performance of Creep-Resistant Magnesium Alloys in Component and Dynamometer Testing of the USAMP Magnesium-Intensive V6 Engine,” presented at the 2008 TMS Magnesium Technology Symposium, New Orleans, LA, March 10, 2008.J. A. Hines, J. E. Allison, B. R. Powell, W. L. Miller, L. J. Ouimet, R. S. Beals, and P. P. Ried, “USAMP Magnesium Powertrain Cast Components Project: Engine Test Results,” presented in the Magnesium Technologies Session of the 2008 SAE Congress, Detroit, MI, April 14, 2008.
3. R. S. Beals, L. Kopka, J. A. Hines, J. E. Allison, R. M. McCune, B. R. Powell, W. L. Miller, and P. P. Ried, “USAMP Magnesium Powertrain Cast Components Project: Engine Test Results,” presented at the 19th Annual Magnesium in Automotive Seminar, International Magnesium Association, Livonia, MI, April 30, 2008.
4. J. A. Carpenter, J. Jackman, R. J. Osborne, B. R. Powell, N. Li, and P. Sklad, “Automotive Research and Development in North America,” *Die Casting Engineer*, [**3**] 54–9, (2008).
5. R. J. Natkin, B. Oltmans, T. J. Heater, J. E. Allison, J. A. Hines, G. K. Tappen, and D. Peiskammer, “Crank Shaft Support Assembly,” US Patent No. 7,288,528 B2, October 23, 2007.

Acknowledgments

The success of this project is due to the dedicated efforts of a large number of team members at Ford, Chrysler, and General Motors. The many other companies and organizations making up the project team are listed in Table 1. The continuing support of our respective companies and the U.S. Department of Energy 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
Alloy Suppliers	AMT, Dead Sea Magnesium, General Motors (GM), Noranda, Norsk-Hydro, Solikamsk, VSMPO-Avisma
Bore Treatment	Gehring, Flame Spray
Casters	Eck, Gibbs, Intermet, Lunt, Meridian, Nemak, Spartan, Thixomat
Casting Modeling	EKK, Flow Science, MAGMAsoft, Technalysis
Coolants	Ashland/Valvoline, ChevronTexaco, Honeywell/Prestone, CCI International
Fasteners	RIBE
Friction Stir Welding	Hitachi
Gaskets	Dana/Victor Reinz
Product Design	Ford, GM, Chrysler, Magna Powertrain
Professional Organizations	International Magnesium Association, North American Die Casting Association
Project Administration	Ried and Associates
Testing Labs	Amalgatech, CANMET, Stork, Westmoreland, Quasar
Tooling	Becker, Delaware Machinery, EXCO, HE Vannatter

C. Ultra-Large Castings of Aluminum and Magnesium (AMD406[*])

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Contractor: United States Automotive Materials Partnership (USAMP)
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 DOE funded contract to the American Foundry Society (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 and aluminum, and a multiple hot-runner direct injection Thixomolding process for magnesium. 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 focus on mechanical properties suitable to thin-wall structural parts while the LTC effort emphasizes low cycle time, and hence, cost for thin-wall parts of modest properties. 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 described.
- 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.

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[*] Denotes project 406 of the Automotive Materials Division of the United States Automotive Materials Partnership, one of the formal consortia of the United States Council for Automotive Research set up by Chrysler, Ford, and General Motors to conduct joint, precompetitive research and development.

- The project will be 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 that 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 (FEA) 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

Large Thin Casting

- On a theoretical basis, the process technical feasibility of making large (e.g., automotive door inner panels) magnesium, and aluminum castings 1.00 mm thick was established.
- Determined processing requirements.
- Developed concepts for the necessary engineering methods, equipment, tooling, and controls.
- Preliminary assessment of the potential cost competitiveness of LTC castings.
- Submitted project "close-out" report.

The Sub-Liquidus Casting Process

- All coupons and test parts were produced in 2007 with evaluation and final report to be completed in June of this year. There has been significant difficulty obtaining a "close-out" report from the staffs at Cosma and the Promatek Research Centre. Appeals to the upper management at Cosma and Promatek will be submitted for assistance in bringing the "close-out" report to completion.

Thixomolding Process to Produce "Shotgun"

- Based upon previous trials, the part was redesigned to be more compatible with the Thixomolding process. Consequently, the tooling was modified accordingly.
- Two significant trials were conducted in 2008 yielding several hundred parts with the expectation that the second trial recently completed will show consistent elongation of 10% or better in critical areas of the "shotgun."
    - The improved design provided major improvement in part ejection.
    - Statistical analysis of data from first trial in 2008 indicates elongation is significantly better than High Pressure Die Casting (HPDC) parts (e.g., 7.01% vs 5.68%). The goal for elongation remains 10% minimum in critical areas of the part. An assessment of this will be determined for the parts produced in the recent second trial.
    - This first trial demonstrated the value of x-ray in assessing the quality of parts in specific areas of interest.

- An economic analysis was completed and is being reviewed and developed.
- The hot runner has been a focus of continued development.

Future Direction

Large Thin Casting

- Integrate the "Project Close-out Report" for LTC into the AMD406 project "close-out" report.

SLC Process

- As noted, the casting trials are complete with the remainder of the work focused on:
  - Characterizing the mechanical properties of the castings.
  - Completing a statistical analysis of Design of Experiments results to determine process capability.
  - Developing conclusions and recommendations for further process improvements.
  - Obtaining a "close-out" report from the project manager at Cosma and at the Promatek Research Centre. Will seek assistance from upper Cosma management and Promatek Research Centre.

Thixomolded Shotgun

- Parts were produced in two trials in 2008. The parts produced during the second trial recently completed will be evaluated first by G-Mag and then by Ford, General Motors (GM), and Canada Centre for Mineral and Energy Technology (CANMET).
- Document all findings in a "Project Close-out Report" which will include assessment:
  - Part design
  - Economics
  - Part properties
  - Full component testing

Introduction

Ultra-Large Casting Rationale

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 (e.g., final reports of references 1, 2, and 3); 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 magnesium or aluminum. 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

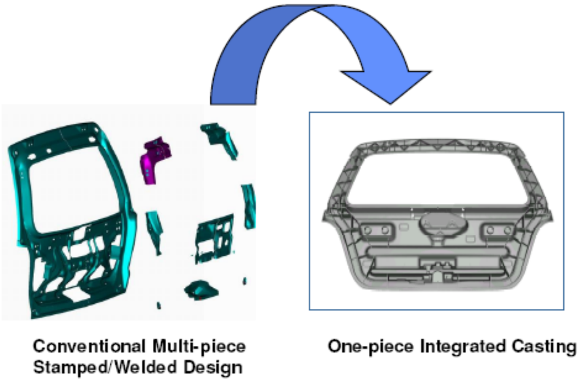

Figure 1. Example of parts integration.

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 magnesium 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 magnesium 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 a ULC project? These particular components are manufactured using the conventional High Pressure Die Casting (HPDC) process, which has some inherent limitations in achieving consistent mechanical properties.

Figure 2. Cast magnesium radiator support.

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 body sides 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, "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 ultra-large castings 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 magnesium die-castings since magnesium 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.

Large Thin Castings

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 semisolid 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) aluminum castings have not become common in the market place. Thin magnesium castings (such as cell 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 aluminum and magnesium castings if they can be made with 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 1 mm 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[4]. 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 is described in the NADCA paper[5]. 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 1 ^{m2} and a substantial area having a thickness of 1 mm. A door inner for a full size pickup truck is an example.
- Cast such panels 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.

The paper, "USCAR/USAMP Large-Thin Casting Project," presented by E.H. Herman won "Best Paper" at the Cast Expo 08 NADCA Casting Congress held May 17-20, 2008 in Atlanta, Georgia. This was followed by a paper published in the July, 2008 issue of *Die Casting Engineer*.

SLC Process Development/ Demonstration

Although the SLC process[6] 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 aluminum 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 1,000 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 test part (Figure 3), geometric features of rib section (Figure 4), step section (Figure 5), and knit line node (Figure 6) evaluation.

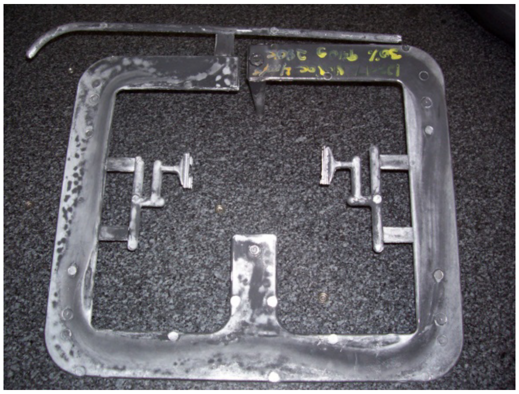

Figure 3. Fluidity test part.

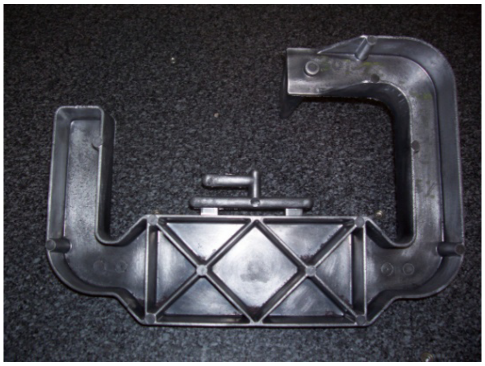

Figure 4. Rib/Waffle geometry.

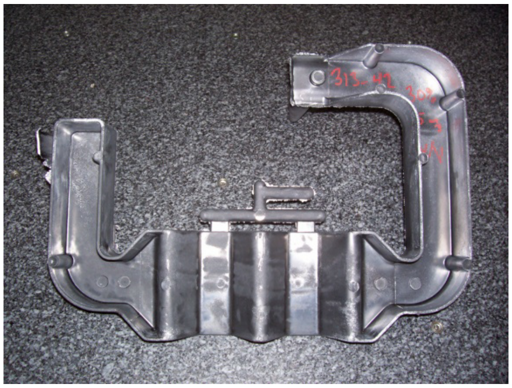

Figure 5. Step geometry.

- Fluidity picture frame (Figure 3) measures 395 mm by 395 mm.
- Flow length from gate through the rib section (Figure 4) is 580 mm and the same holds for the step section. For example, the metal flows from the gate through the grid section and exits the grid section after flowing approximately 580 mm.

Figure 6. Knit line node geometry.

- 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 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.

SLC Experimental Results

No new results have been reported since 12/31/07, but the conclusions previously established will be repeated below.

SLC Conclusions

- Low flow velocity and short flow distances; thus, hot runner technology (Mg) and multiple in-gates for aluminum 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 aluminum and magnesium 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 magnesium shotgun. The Thixomolding process has the potential to produce magnesium 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. Magnesium 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 magnesium casting produced by the HPDC process. For such a part, a full evaluation of the component can be conducted.

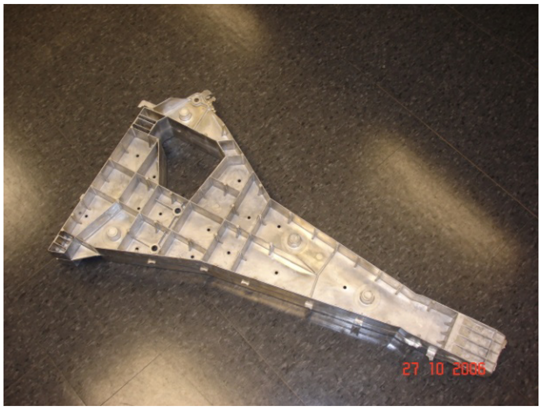

Figure 7. F-Series “Shotgun”.

Several trials have been performed in a continuous effort to improve operation (e.g., part ejection difficulties) and part quality (e.g., elongation). For 2008, the part design was significantly modified to reach the project objectives.

Casting Trials

As a result of the trials conducted in 2007, the part design and the tooling were significantly modified to provide:

- Improved part ejection.
- Better metal flow.
- Reduction in total metal required for the part such that metal may be available for overflows and charge cylinder is not required to near end of stroke.

The part design prior to 2008 is shown in Figure 7 with the modified design shown in Figure 8 and Figure 9. Note that ribs have been eliminated on one side to reduce charge. It should be noted that the ribs for the modified shotgun only exist on one side. The shotguns installed in cab and prepared for testing are shown in Figure 10. During the first trial the following conclusions were made:

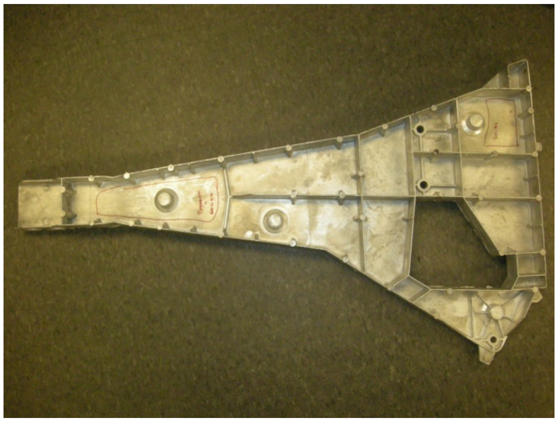

Figure 8. F-Series “Shotgun” revised.

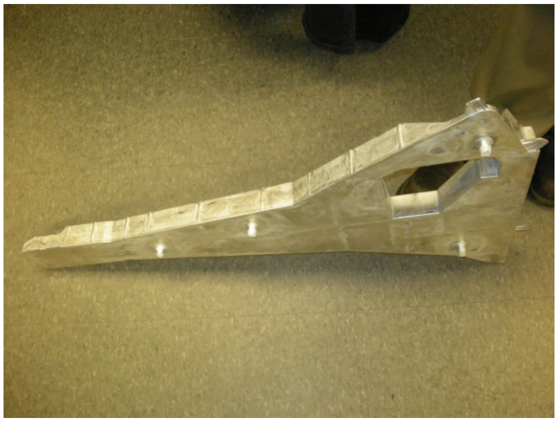

Figure 9. F-Series “Shotgun” revised.

- Part ejection and process interruptions greatly improved.
- Cycle times changed from 90 seconds to 70 seconds with opportunity to further improve.
- Part-to-part consistency improved.
- Packing pressure increased from 2,000 to 5,000 psi.
- Overflows were not utilized.
- Further improvements in the design must be made to be more favorable to magnesium molding.

Figure 10. Full cab with magnesium shotguns.

- Shorter fill times increased difficulty for firing 4 drops simultaneously.
- Entrapped die lube and air were not fully expelled.
- Location of hot drops is not optimized for providing best quality in crumple zone.

For the parts produced in this first trial, Ford conducted a statistical analysis comparing observed elongation with x-ray quality. This analysis confirmed that x-ray is an effective tool to identify acceptable parts/unacceptable parts. For the samples examined, it was shown that the mean elongation for parts having an x-ray quality of level 1 exhibited a mean elongation of 9.6%, level 2 a mean elongation of 6.2%, and level 3 a mean elongation of 3.7%.

Based upon the results of this first trial, it was clear that overflows provide a major advantage in removal of entrapped air. Although some significant improvements to the part are preferred to minimize air entrapment, overflows will be opened for this second run and are expected to improve part quality. Over 300 parts were produced during this second run conducted in December and they are undergoing analysis first at G-Mag and Husky, followed by evaluation at Ford, General Motors (GM), and CANMET. It also must be noted that overflows were considered at the beginning of the effort but so much material was required in the part design that none was available for overflow.

Conclusions

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

- During 2007, dimensional control was shown to be very acceptable.
- Critical property (elongation) fell short of expectations (i.e., seeking 10%) in 2007, with some improvement noted in the first trial of 2008 working with the revised shotgun design.
- The revised part design enabled much improved ejection of parts.
- X-ray can clearly distinguish between acceptable and unacceptable parts.
- Solids content varies significantly over a relatively small area of the part and around the same drop. This is an indication that the drops do not always open to flow.

In this second trial, the die overflows were opened. These parts will be evaluated at G-Mag/Husky using x-ray, porosity, and tensile, yield and elongation measurements. A group of 65 parts will be sent to Ford for x-ray evaluation. These same parts will be distributed to GM, Ford, and CANMET for a more thorough evaluation of tensile, yield, and elongation. It is anticipated that like all previous trials, properties will continue to improve and presumably hit the 10% elongation target in buckling zone. A production cost analysis was submitted but further changes are required before data can be communicated. Cost analysis was done for 115k, 178k, and 268k parts per year volume.

After receiving the final “close-out” reports for Thixomolding and SLC efforts, an integrated “close-out” report will be prepared for all of AMD406 efforts.

Presentations/Publications/Patents

1. E. Herman, “USCAR/USAMP Large Thin Casting Project,” Cast Expo 08 NADCA, Atlanta, Georgia, May 17–20, 2008. “Best Paper” award.
2. E. H. Herman, USCAR/USAMP Large-Thin Casting Project, Die Casting Engineer, pp. 52–55, July 2008.

3. Ultra Large Casting (USCAR), “Shotgun,” awarded 1st Place in the Process Category, IMA 2007 Awards Competition, Vancouver, BC, May 15, 2007.
4. M. Maj, “Ultra Large Castings for Lightweight Vehicle Structures,” IMA Automotive Seminar, Laurel Park Manor, Livonia, MI, March 28, 2007.
5. M. Maj. “Ultra Large Castings for Lightweight Vehicle Structures,” TMS 2007 Annual Meeting, Orlando, FL, 2/21–3/1, 2007.

References

1. *Development of a Casting Process for Ultra-Large Automotive Components,* Final Report, Subcontract No. 86X-SU545C, April 28, 2000.
2. American Foundry Society (AFS) Project ORNL-ULC, July 16, 2002.
3. AFS Project ORNL-ULC-II, July 30, 2003.
4. Education Program Master Plan, NADCA.
5. USCAR/USAMP Large-Thin Casting Project NADCA, *Die Casting Engineer*, July 2008, pp. 52–55.
6. “Sub-Liquidus Casting: Process, Concept and Product,” J. Jorstad, M. Thieman, R. Kamm, M. Loughman, and T. Woehlke, 2003 *AFS Transactions*, No. 03-162

D. High Integrity Magnesium Automotive Castings (AMD 601*)

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Contractor: United States Automotive Materials Partnership (USAMP)
Contract No.: DE-FC26-02OR22910 through the 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 Mg control-arm components for static and/or vehicle testing.
- Evaluate potential of emerging Mg castings technologies, specifically the ablation and T-Mag processes.

Approach

- The approach of the High Integrity Magnesium Automotive Castings (HIMAC) 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 low-pressure permanent-mold and squeeze-casting processes for the production of Mg structural castings.
- Two new emerging casting processes (ablation and T-Mag) will be investigated.
- The project aims to facilitate production of Mg components requiring geometries and properties not possible with existing high pressure die casting (HPDC) process limitations.
- 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.

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[*] Denotes project 601 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. See www.uscar.org.

Accomplishments

- Cost expenditures match original budget numbers, and in-kind support meets or exceeds forecasted numbers.
- The HIMAC Project team has 43 active participants from the Big 3; industry, academia, and Canada Centre for Mineral and Energy Technology (CANMET).
- Project participants support the project functions including visits to project member's facilities and universities, and participation in conference calls and quarterly review meetings (QRM).
- Four new Mg casting processes have been or are being developed. Rear lower control arms have already been produced from three of the processes.
- Seven different universities are actively involved in the HIMAC Project, including students from undergraduate to Ph.D. levels.
- Microstructure properties and modeling techniques are being identified for the different types of Mg alloys that have already been cast.
- The typical Mg control arm that is being evaluated is shown in Figure 3.
- The Magnesium Vision 2020 document (developed by the Structural Cast Magnesium Development [SCMD] Project) is used as reference by the HIMAC Project team as the new Mg casting processes are developed.
- The electromagnetic pump (Task 6) is completed and is being fitted for the low-pressure permanent mold (LPPM) machine at CMI Equipment.

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.
- Installation and use of the electromagnetic pump in the LPPM system will be a new innovation in the manufacture of Mg castings.
- The HIMAC Project team will provide Mg control arm castings from all four new casting processes by the end of the June 2009 for testing and evaluation.
- All original statement of work (SOW) tasks will be completed in accordance with the original project timeline and budget figures. However, the HIMAC Project team has discovered some important R&D atures of these three processes that could use additional funding to develop them to their full potential, especially in the understanding of grain refinement and modeling characteristics.

Introduction

The overall introduction for this project changed when the original SOW was revised to include additional information on the T-Mag process. As each report is submitted to 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 HIMAC Project is well on its way to support this goal.

The HIMAC Project addresses near- and mid-term technical barriers that currently inhibit Mg casting production that 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 required to reduce the cost of Mg components and enable sustainable production requirements. The HIMAC Project has already started to address various aspects of these three key issues.

Development of Casting Tools

Developed technologies and tools 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 metal casting development needs identified in the published *Magnesium Vision 2020* document. Understanding and eliminating production barriers that affect the affordability of cast Mg components.

Casting Process Development

Developed 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) was built and operated briefly by CONTECH. However, they recently closed the facility due to economic conditions.

Figure 1. CONTECH squeeze casting cell.

An existing Squeeze Cast Production machine at Meridian Technologies Inc. (Figure 2) was activated to support the HIMAC Project.

Figure 2. Meridian squeeze casting cell.

Magnesium control arms have already been produced at Meridian and are being evaluated.

A low pressure casting cell (Figure 3) was built by CMI E & E for the HIMAC Project.

Figure 3. CMI E & E low pressure casting cell.

Magnesium control arm castings (Figure 4) have been produced from this cell and are being evaluated.

Figure 4. Magnesium control arm.

Tooling is currently being built for the T-Mag Casting Process located in Australia (Figure 5). Casting will be available for testing and evaluation by June 2009.

Figure 5. T-Mag casting cell.

Infrastructure Development

Development of all four casting processes and tools will include industry participation by automotive suppliers currently producing aluminum components (Tasks 1, 2, 7); include the development of equipment uniquely suitable for the production of Mg components (Task 2, 6); and provide for the 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 an Mg control arm by low-pressure cast, squeeze cast, and two new emerging casting processes (ablation and T-Mag). Control arms will be delivered for static and/or vehicle testing from these processes by June of 2009.

To support the achievement of these processes, the project is divided into eight tasks. These tasks will address key technology barriers that limit casting of Mg automobile suspension, 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

Note: Steering committees within the HIMAC Project have been formed to independently assist the core project team in the achievement of these tasks.

Conclusions

The HIMAC 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, 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 HIMAC Project will provide technical support to the Magnesium Front End Research and Development Project (AMD 604). (See report 6.C.)

Presentations/Publications/Patents

1. Beckermann, “Prédiction of Porosity and Hot Tears in Magnesium Casting.” Materials Science and Technology (MS&T), 2007 Conference, Detroit, MI, September 2007.

2. Y. Xue, M. F. Horstemeyer, D. L. McDowell, H. El Kadriri, and J. Fan. “Microstructure-based multistage fatigue modeling of cast

AE44 magnesium alloys," *Int. J. of Fatigue* **29,** 666–76 (2007).

3. El Kadiri, Y. Xue, M. F. Horstemeyer, B. Jordan, and P. Wang. "Fatigue Crack Growth Mechanisms in a Die Cast AM50 Alloy." *Acta Materialia* **54,** 5061–76 (2006).
4. Greg Woycik, CMI Equipment & Engineering. "Low Pressure Casting of Magnesium Alloys for Automotive Components." American Foundry Society-111th Metalcasting Congress, May 15–18, 2007.
5. David Weiss, Eck Industries, Inc. "Magnesium Casting Technology Update." American Foundry Society-111th Metalcasting Congress, May 15–18, 2007.
6. Brian Szymanowski, CONTECH. "HIMAC Magnesium Squeeze Casting Update." American Foundry Society-111th Metalcasting Congress, May 15–18, 2007.
7. Bruce Cox, DaimlerChrysler NA. "High Integrity Magnesium Automotive Components (HIMAC)." American Foundry Society-111th Metalcasting Congress, May 15–18, 2007.
8. M. Pokorny, C. Monroe, C. Beckermann, L. Bichler, and C. Ravindran. "Prediction of Hot Tear Formation in a Magnesium Alloy Permanent Mold Casting." *Int. J. Metalcasting*, Vol. 2, No. 4, 41–53 (2008).
9. American Foundry Society (AFS) 6th International Conference on Permanent Mold Casting of Aluminum and Magnesium, Frisco, TX, February 11–12, 2008.
10. G. G. Woycik, CMI Equipment and Engineering, Inc., AuGres, MI; M. Marlatt, Marlatt Technologies, Three Lakes, WI. "Low Pressure Permanent Mold Casting of a Magnesium Lower Control Arm." (Publication and Presentation).
11. Randy Sheng, Sarah Chen, and Jagan Nath, General Aluminum, Madison Heights, MI. Sponsored Research: "Low Pressure Casting Process Simulation and Tooling Design for HIMAC's Magnesium Automotive Control Arm (08-148)." CastExpo '08, May 17, 2008, Atlanta, GA. (Publication and Presentation).
12. Leonard Winardi, Preston Scarber, and Robin Griffin, University of Alabama-Birmingham, Birmingham, AL; David Weiss, Eck Industries Inc., Manitowoc, WI. "Comparison of Gas Evolution Results from Chemically Bonded Cores In Contact with Magnesium and Aluminum Melts (08-048)." (Publication and Presentation).
13. Richard Jacques, CONTECH U.S. LLC, Portage, MI; John Jekl, Meridian Magnesium, Strathroy, ON, Canada (2 Presentations). "Development of the Squeeze Cast Process for the USCAR HIMAC Project. (08-165)."
14. Michael Marlatt, Marlatt Technologies, Three Lakes, WI; Gregory Woycik, Woycik Metallurgical Consulting LLC, Lapeer, MI; Chung-Whee Kim, EKK Inc., Farmington Hills, MI: (2 Presentations). "Low Pressure Casting of a Magnesium Control Arm (08-166)."

Acknowledgements

The HIMAC Project team has cast Mg castings from all four of the new casting processes, and completed the casting of the Mg control arms from three of the processes. This success would not have been possible without the support and help from: the DOE; the U.S. Council for Automotive Research (USCAR) steering committee; the U.S. Automotive Materials Partnership (USAMP) Automotive Metals Division (AMD) Board; the Big 3; the Canada Centre for Mineral and Energy Technology (CANMET); and the technical societies, and industrial and academia teams that support this project.

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 chairman appreciates the support from all of the teams mentioned above.

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, macrosegregation, 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, macrosegregation, mushy zone) in Mg cast parts with the objective of developing new or improved casting methods (considering gravity-poured method first) for these alloys.

Accomplishments

- Conducted Mg alloy gravity-poured casting experiments at Oak Ridge National Laboratory.
- Performed microstructural analysis of cast Mg alloys (AZ91 and AE42).
- Developed a model for porosity formation during solidification of Mg alloy AZ91.
- Developed a model for dendrite growth during solidification of AZ91 Mg alloy.

Future Direction

- Complete analysis of porosity and secondary dendrite-arm spacing (SDAS) in cast samples and correlate with cooling rate.
- Obtain physical properties of AE42 for modeling purposes.
- Model development for porosity formation for AE42.
- Obtain second dendrite-arm spacing for different cooling rates using optical microscopy.
- Complete validation of AZ91 and AE42 models through experimental results.

Introduction

Magnesium cast alloys, such as AZ91 and AE42, are gaining increasing attention in the struggle for weight saving in the automobile industry [1]. However, in many cases the consistent production of sound Mg castings is marred by the stubborn persistence of some defects that are difficult to remove: porosity, macrosegregation, oxide entrainment, irregularity of microstructure, etc. The formation of microporosity in particular is known to be one of the primary detrimental factors controlling fatigue lifetime and total elongation in cast light-alloy components.

Much effort has been devoted to modeling and experiments on porosity formation in the last 20 years. More recently, rather sophisticated models have been developed to include the effect of pores on fluid flow (three-phase transport) [2], multiscale frameworks that consider the impingement of pores on the microstructure [3], and effects of finite-rate hydrogen (H) diffusion in the formation of pores [4]. A recent review on the subject of computer simulation of porosity and shrinkage-related defects has been published by Stefanescu [5]. New mechanisms of pore formation based on entrainment of oxide films during the filling of aluminum (Al) alloy castings have been identified and documented [6–11]. Oxide film defects are formed when the oxidized surface of the liquid metal is folded over onto itself and entrained into the bulk liquid. A layer of air is trapped between the internal surfaces of the oxide film, which leads to the porosity formation in the solidified castings. The entrainment process due to surface turbulence is usually rapid, on the order of milliseconds; therefore, the time is very limited to form new oxide film on the fresh surface, so the entrained oxide film can be very thin, on the order of nanometers [6].

Four parts are included in this work: (1) gas porosity model in Al and Mg alloys; (2) porosity and oxide films in AZ91, (3) porosity and oxide films in AE42, and (4) dendrite growth model in Mg alloy solidification.

The results presented in this report are relevant to a gravity-pour casting process for which we develop a porosity model. This model is not applicable to high-pressure die casting, which involves flow conditions and a time scale vastly different from the one treated by the current solidification model. The role of oxide films in adding porosity formation could carry over to other low-pressure permanent mold and direct chill casting processes.

Gas Porosity Model in Al and Mg Alloy

A numerical model of H porosity formation during solidification was developed and applied to Al alloy A356 and Mg alloy AZ91. The model (named MULTIA) solves the conservation equations of mass, momentum, and energy and each alloy component within a continuum framework in which the mushy zone is treated as a porous medium of variable permeability. To predict whether microporosity, the solidification shrinkage due to different phase densities, occurs, the concentration of gas-forming elements and their redistribution by transport during solidification were later added to the model. 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 (references [12] and [13]).

Modeling results of the distribution of pore volume fraction and pore size in A356 are compared with published works. In view of the limited availability of experimental data for Mg alloy gravity-poured castings, the model is used to make a comparison study of porosity formation between Al alloy A356 and Mg alloy AZ91, assuming similar casting conditions. The minimum initial H content that leads to the formation of gas porosity is compared for both alloys. The two parameters of the porosity model, initial pore size and concentration of inclusions, are taken from the A356 data. We acknowledge that these are rather arbitrary assumptions, but in view of the lack of more suitable data, our purpose is only to observe how porosity in AZ91 would form and evolve under these conditions and make a side to side comparison with A356.

Figure 1 shows the variation of pore volume fraction and pore diameter versus cooling rate in the solidified casting of A356 Al alloy for an initial H content of 0.11 cc/100g.

In Figure 1, the small dots are calculated values that span throughout the casting; each dot represents the pore volume fraction or pore diameter calculated at a mesh node in the casting. A least squares fit of the calculated values is also shown as a solid black line. The experimental data of Fang and Granger [14] are indicated as larger circular dots; these were taken by manual reading from their paper, so bars estimating possible reading error are added. The experimental 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.

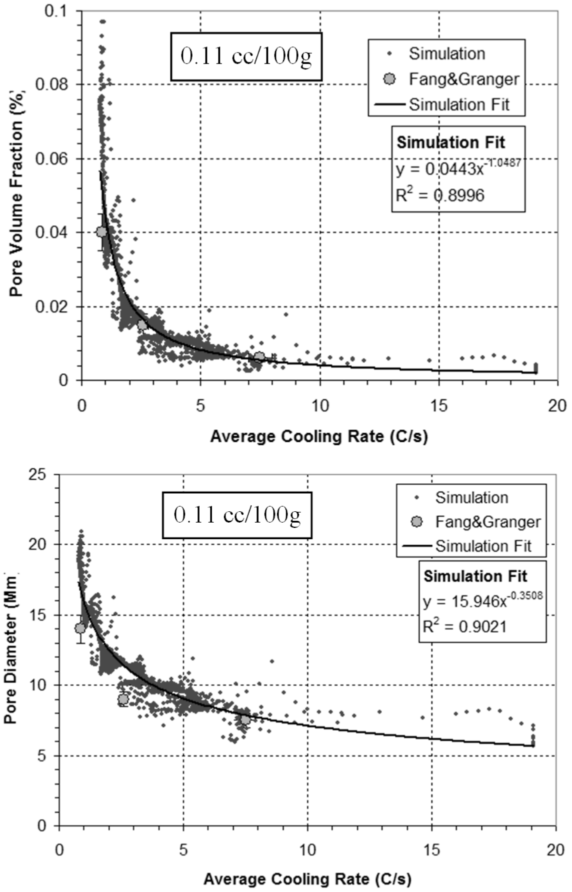

Figure 1. Pore volume fraction and pore diameter vs cooling rate for A356 (H content: 0.11 cc/100g).

Figure 2 shows the variation of pore volume fraction and pore diameter vs cooling rate in the solidified casting of AZ91 Mg alloy for an initial H content of 17.72 cc/100g. Similarly to Figure 1, the small 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 least squares fit of the calculated values is also shown as a solid black line. Both pore volume fraction and pore diameter show a similar trend between AZ91 and A356, suggesting that porosity develops similarly in both alloys. However, the minimum initial concentration of H to form pores in AZ91 is much higher than in A356. The high initial H content (~16 ppm) needed to form porosity in AZ91 is attributed to the high solubility of H in this alloy.

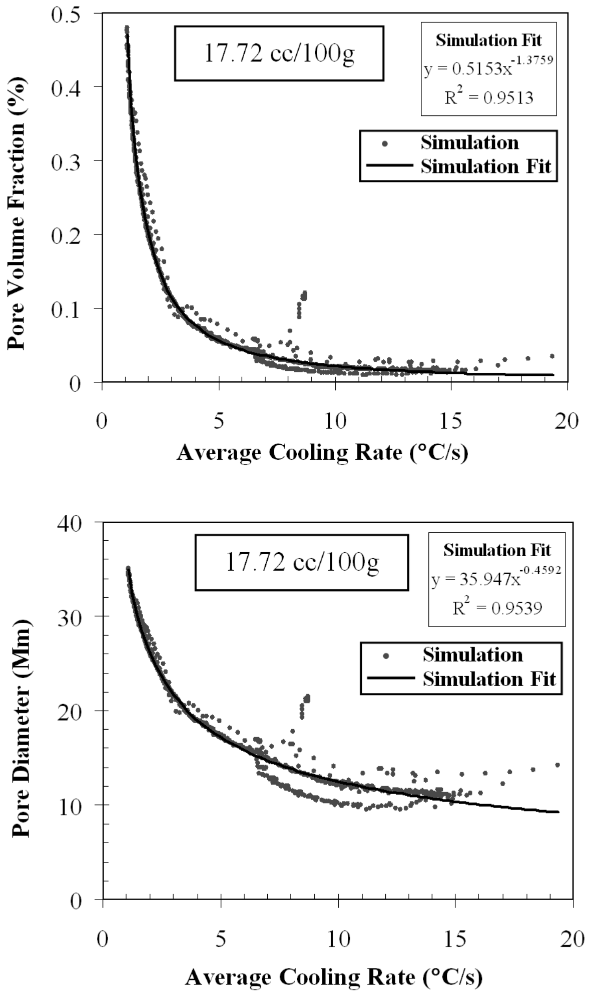

Figure 2. Pore volume fraction and pore diameter vs cooling rate for AZ91 (H content: 17.72 cc/100g).

The porosity growth rate, R_p (in microns per cubic centimeter per hundred grams), due to the change of the initial H content in the liquid alloy is defined as

$$R_p = \frac{d_1^p - d_2^p}{C_1^H - C_2^H} \quad , \qquad (1)$$

where d_1^p and d_2^p are the pore diameters at a certain cooling rate for different initial H content, C_1^H and C_2^H, respectively. Figure 3 shows the porosity growth rate as a function of the average cooling rate when the initial H content increases in the amount of 0.14 cc/100g for A356 and AZ91 under the same casting conditions. It is observed that the porosity growth rate for AZ91 is much smaller than for A356, which is expected because the diffusion coefficient of H in liquid Mg is smaller than that in liquid Al, as shown in Figure 4.

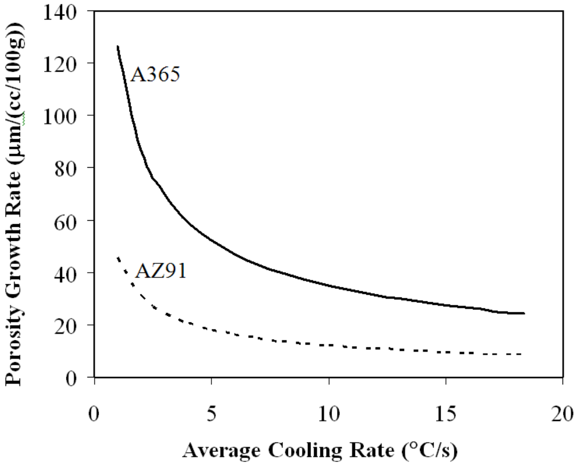

Figure 3. Porosity growth rate vs cooling rate when the initial H content increases in the amount of 0.14 cc/100g for A356 (from 0.11 to 0.25 cc/100g) and AZ91 (from 17.72 to 17.86 cc/100g).

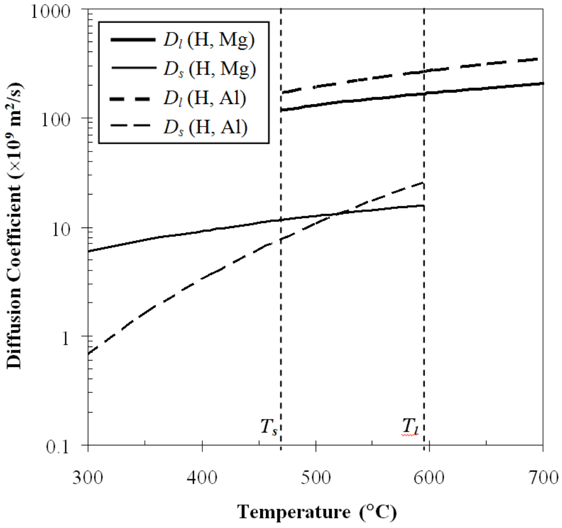

Figure 4. Diffusion coefficient of H in Mg and Al as a function of temperature [16].

Porosity and Oxide Films in AZ91

In this study, we examined the microstructure of Mg alloy AZ91 ingots gravity poured in plate graphite molds. Temperature information during cooling was acquired with type K thermocouples at 60 Hz in two locations for each casting. The microstructure of samples extracted from the regions of measured temperature was then characterized using optical metallography, tensile tests, and scanning electron microscopy (SEM) of the fracture surfaces. The nature of oxide film and porosity defects in AZ91 was investigated.

Porosity was the major defect observed in the tested specimens. Pores ranging in size from 100 µm to 500 µm were found in many of the polished surfaces. Figure 5 shows typical pore morphology at a location close to the thermocouple in the AZ91 C1 sample [Figure 5(a)]. A magnified view [Figure 5(b)] reveals dendrites protruding into the pore as well as pieces of oxides on the surface of the pore. Energy-dispersive X-ray (EDX) spectroscopy shows a threefold increase of the oxygen content inside the pore compared with the surrounding matrix. [15]

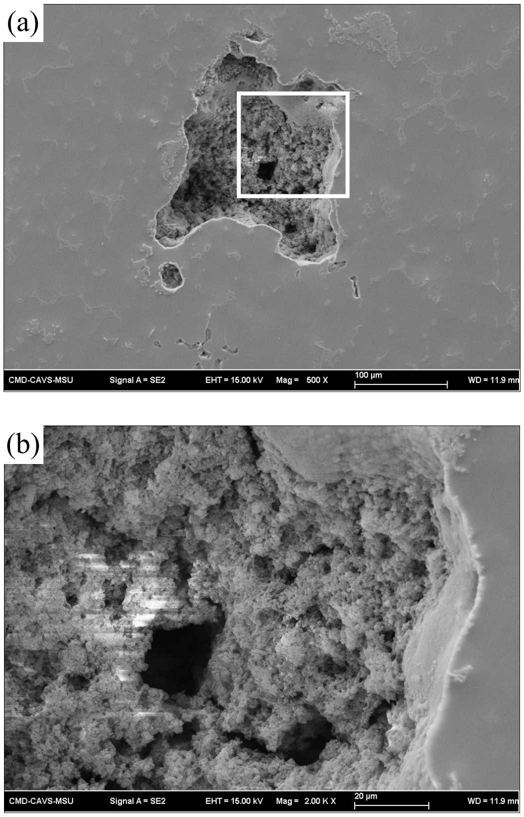

Figure 5. (a) Typical pore morphologies formed at the location close to the thermocouple in casting AZ91, sample C1; (b) higher magnification (2000×) of image (a).

This pore was most probably caused by interdendritic shrinkage; however, the presence of oxides might suggest also a pore formed by an entrained double oxide that was torn apart by shrinkage-induced shear forces. The details of fracture surfaces of tensile test AZ91 samples are shown in Figures 6 and 7. Figure 6 shows two symmetrical oxide films on either side of a fracture surface. This agrees well with the observation by Griffiths and Lai [17] for pure Mg castings. A magnified view of the oxide region (Figure 7) reveals a pleated surface similar to that observed in double oxide films in Al alloys.

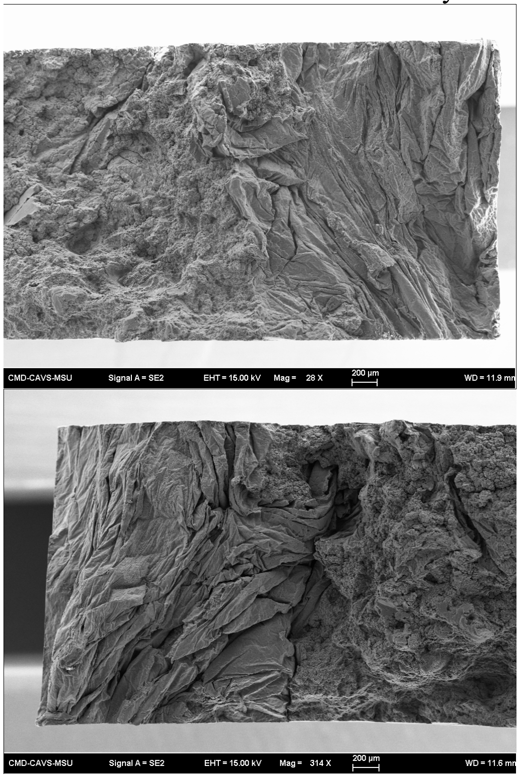

Figure 6. Scanning electron microscope images of oxide films on the two sides of the fracture surfaces of a tensile test specimen taken from AZ91, sample C1.

Porosity and Oxide Films in AE42

In this study, we examined the microstructure of Mg alloy AE42 ingots gravity poured in plate graphite molds. Two graphite plate molds and a ceramic cylindrical mold were selected to produce a wide range of cooling rates. Temperature information during cooling was acquired with type K thermocouples at 60 Hz in two or three locations for each casting. The microstructure of samples extracted from the regions of measured temperature was then characterized with optical

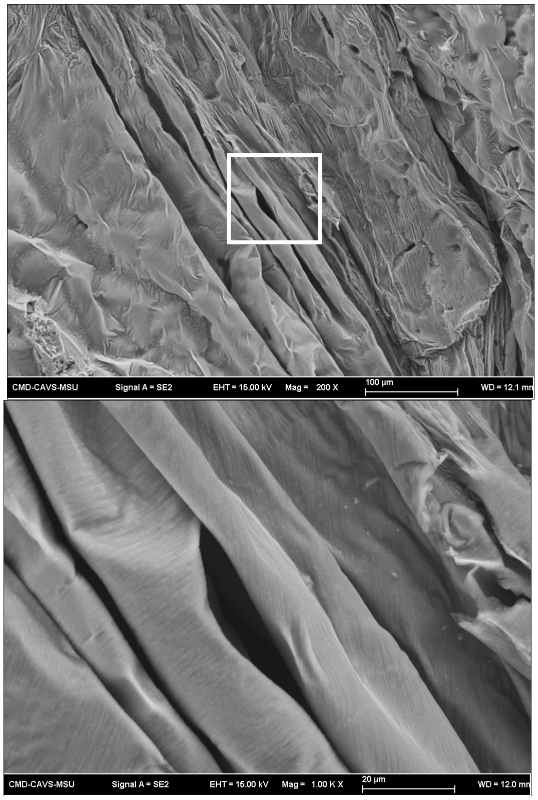

Figure 7. Higher magnification views of the oxide film found on the fracture surface shown in Figure 6.

metallography. This work investigated the nature of oxide film and porosity defects in AE42 for different cooling rates.

The tested AE42 alloy composition was Mg, 3.96% Al, 0.35% Mn, 0.01% Si, 0.001% Ni, 0.007% Zn, 0.0003% Fe, 0.0008% Cu, and 8 ppm Be. The furnace charge was in the form of prealloyed ingot. The weight of the melt was 8 kg, and the alloy was melted in an electrical resistance furnace. For protection, Ar and CO_2 + 3% SF_6 were used as cover gases. The pouring temperature for AE42 was roughly 680 to 700°C. No degassing procedures were used. All castings were poured from one melt. The melt was poured directly from the crucible to minimize temperature decrease during pouring.

The pouring temperature was about 715, 695, and 725°C for casting types C, A, and E. All the molds were not preheated and were coated with boron nitride. To assess the reproducibility of the results, two molds were used for each type of casting. Temperature information was acquired with type K thermocouples at approximately 60 Hz. The cooling curves are shown in Figure 8. The cooling curves are labeled in the following format: xn_m, where x is a letter, indicating the mold type; n indicates casting number (1 or 2); m indicates thermocouple (1 or 2) for molds A and E and position of thermocouples for molds type C (b—bottom of casting, c—center of casting). The cooling curves show an excellent reproducibility. The temperature information measured by the thermocouple near the top of the casting was discarded because of turbulence in this region. As shown in Figure 8, the cooling rates for AE42 alloy castings were approximately 20, 5, and 1°C/s for molds A, C, and E.

A common feature found in all the samples is that the pores were observed to be smaller at higher cooling rates. Porosity was the major defect observed in the tested specimens. Figure 9 shows long pieces of oxide films, some longer than 1 mm in the sample E1-1 from the mold type E with cooling rate of 1°C/s. The distinct precipitation upon both sides of the film might suggest the former existence of a double oxide that was later torn open, with the higher precipitation occurring on the wetted side. It is interesting to note that oxide films were found only in the samples from ingots cast at the lowest cooling rate. This fact needs confirmation by examining more samples.

Dendrite Growth Model in Mg Alloy

In this work, a coupled cellular automaton–finite element model was developed to simulate dendrite growth during the solidification of Mg alloy AZ91. The model was applied to the simulation of small specimens with equiaxed and columnar grain growth. The influence of cooling rate and some kinetics parameters on the grain morphology were also discussed as follows.

A single nucleus is set at the calculation domain center to start the grain growth process during solidification. The calculation domain has uniform initial temperature and composition. Constant heat flux (10 kw/m^2) is imposed at the four walls. The nucleus has an initial composition kC_0 and preferred growth orientation of zero degree with

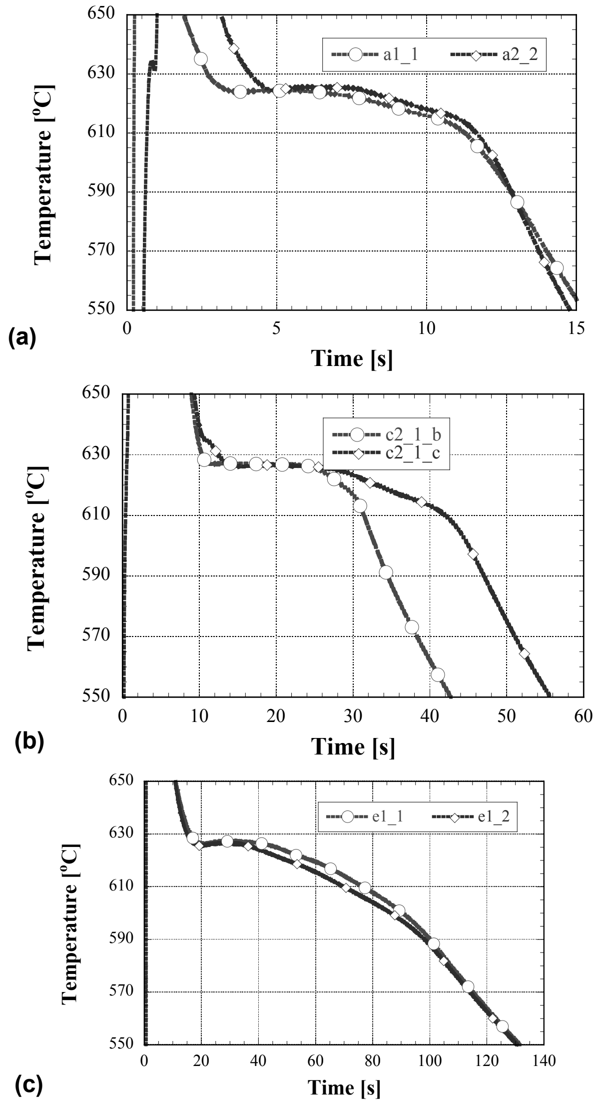

Figure 8. Cooling curves for Mg alloy AE42 castings. (a) mold type A, (b) mold type C, and (c) mold type E.

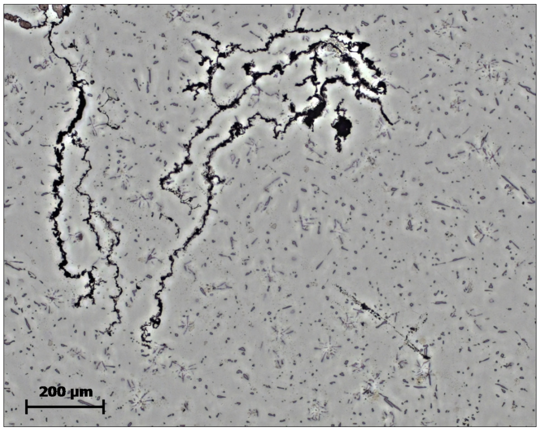

Figure 9. Typical micrographs for Mg alloy AE42, sample E1-1, showing porosity and oxide films.

respect to the horizontal direction. The square domain has a 400 × 400 mesh and a side length of 200 µm. Figures 10(a), (b), and (c) present the simulated evolution of equiaxed dendrite growth at different holding times of 0.0212s, 0.0424s, and 0.0636s, respectively. It can be seen that in the early stage of solidification, the dendrite develops the primary arms which follow the crystallographic orientations [Figure 10(a)]. As solidification proceeds, the primary arms become larger and the secondary arms begin to occur [Figure 10(b)]. With further solidification, some tertiary dendritic arms form from the secondary arms [Figure 10(c)].

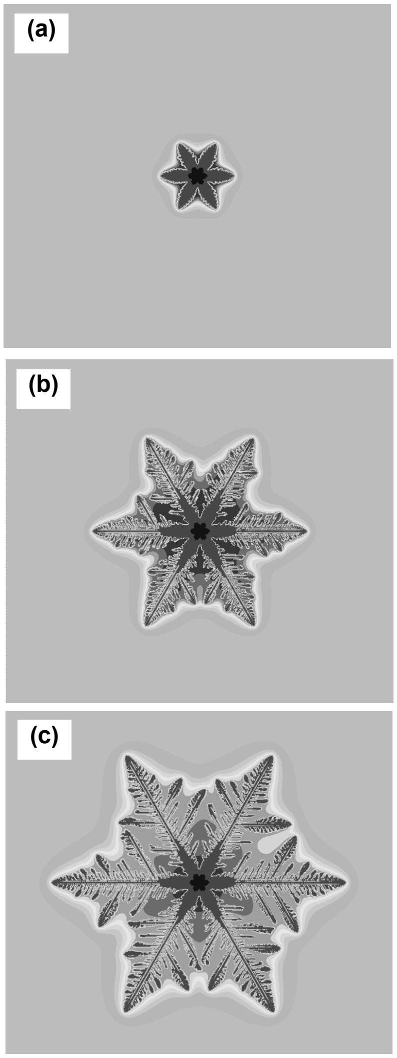

Figure 10. Solute map at different holding times. (a) 0.0212s, (b) 0.0424s, and (c) 0.0636s.

Two different heat flux boundary conditions were imposed on the walls to study the influence of cooling rate on dendrite morphology (Figure 11). Large heat flux corresponds to high cooling rate [Figure 11(a)]. An increase of the heat flux makes the dendrite grow faster and the secondary arms longer. As Figure 11(b) shows, when the heat flux is 5 kW/m^2, only a few secondary arms occur. In addition, a large heat flux makes the grain grow faster, so more solute is released from the solid and there is less time for solute diffusion, which produces a high solute composition in the liquid. The growth of columnar dendrites was also simulated for the same Mg alloy directionally solidified with heat flux applied on the left wall. The calculation domain has a 400 × 200 mesh and dimensions of 100 × 50μm. Two nuclei were placed at the left wall with crystallographic orientation aligned with the temperature gradient.

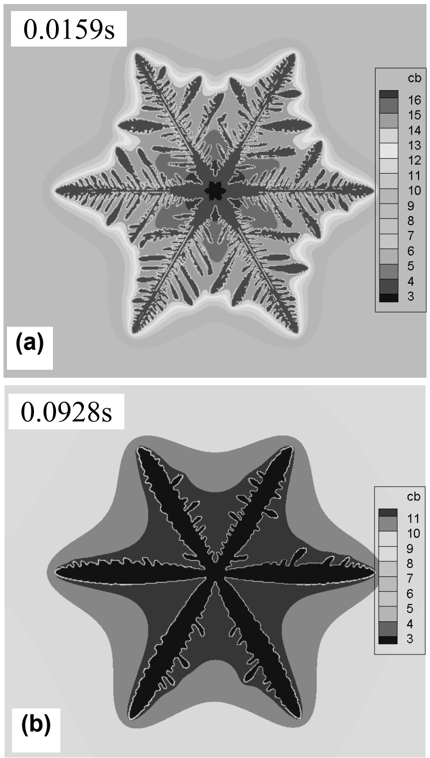

Figure 11. Solute map with heat flux of 20kW/m^2 (a) and 5kW/m^2 (b).

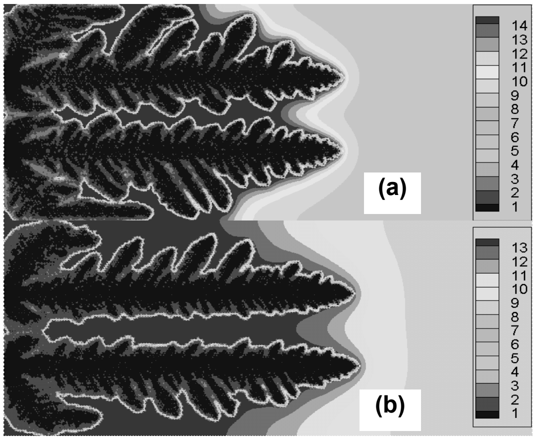

Figure 12. Solute map with heat flux of 80kW/m^2 and holding time 0.0339s (a) and 20kW/m^2 with holding time 0.1166s (b).

Figures 12 (a) and (b) present the simulated evolution of columnar dendrites with heat fluxes of 80kW/m^2 and 20kW/m^2, respectively. A larger heat flux produces a steeper temperature gradient, which leads to thinner dendrites. The primary arms whose morphology orientation is not parallel to the heat transfer direction will be stopped by the growth of the arm parallel to temperature gradient. The growth of some main arms can also be stopped by nearby dendrites. High liquid composition between the two columnar grains due to the small separation between them makes the secondary arms comparatively short.

Conclusions

The following conclusions were derived in this study.

- A solidification-porosity model was developed based on transport of inclusions and H diffusion pore growth. The model was validated for A356, and simulations were performed for AZ91.
- A dendrite growth model based on the cellular automaton technique was developed which shows good potential to deal with the still unsolved problem of mesh-induced anisotropy in hexagonal systems like Mg alloys.
- Gravity poured castings of AZ91 and AE42 were prepared in graphite and ceramic molds of various sizes. Analysis of microstructural data (in progress) should provide an estimate of correlation of porosity with cooling rate, useful for model verification (though no H content data are available).
- Microstructural analysis of AZ91 and AE42 samples revealed the presence of oxide films

similar to those found in Al castings, including some in the interior surface of pores.

Presentations/Publications/Patents

1. S. D. Felicelli et al., "A model for Gas Microporosity in Aluminum and Magnesium Alloys," *Metallurgical and Materials Transactions B* (accepted).
2. L. Wang et al., "Oxide Film and Porosity Defects in Magnesium Alloy AZ91," 2009 TMS Annual Meeting & Exhibition, Shaping Casting: Third International Symposium, San Francisco, California, February 15–19, 2009 (accepted).
3. L. Wang et al., "Interdependence between Cooling Rate, Microstructure and Porosity in Mg alloy AE42," 2009 TMS Annual Meeting & Exhibition, Magnesium Technology, San Francisco, California, February 15–19, 2009 (accepted).
4. H. Yin and S. D. Felicelli, "Simulation of microstructure evolution during solidification of magnesium alloys," *Materials Processing Fundamentals*, 2009 TMS Annual Meeting & Exhibition, San Francisco, California, February 15–19, 2009 (accepted).
5. J. C. Heinrich et al., "Projection method for flows with large local density gradients. Application to dendritic solidification," *International Journal for Numerical Methods in Fluids*, **57**(9), pp. 1211–1226 (2008).
6. S. Poola et al., "A re-examination of factors affecting porosity gradients in unidirectionally solidified samples," *Transactions of the American Foundry Society,* **116**, pp. 157–168 (2008).
7. S. D. Felicelli, E. Escobar de Obaldia, and C. M. Pita, "Simulation of hydrogen porosity during solidification," *Transactions of the American Foundry Society*, **115**, paper 07-078, pp. 1–13 (2007). (BEST PAPER AWARD.)
8. S. Felicelli et al., "An International Collaboration for the Study of Defects in Castings," *2008 ASEE Annual Conference & Exposition*, Pittsburgh, Pennsylvania, June 22–25, 2008.

References

1. C. H. Caceres et al., "Effects of solidification rate and ageing on the microstructure and mechanical properties of AZ91 alloy," *Materials Science and Engineering A*, **325**, pp. 344–355 (2002).
2. A. S. Sabau and S. Viswanathan, *Metall. Mater. Trans. B*, **33B**, pp. 243–255 (2002).
3. P. D. Lee et al., *Mater. Sci. Eng. A*, **365B**, pp. 57–65 (2004).
4. K. D. Carlson, Z. Lin, and C. Beckermann: *Metall. Mater. Trans. B*, **38B**, pp. 541–555 (2007).
5. D. M. Stefanescu, *Int. J. Cast Met. Res.*, **18**, pp. 129–143 (2005).
6. John Campbell, *Castings 2nd ed.* (Butterworth-Heinemann, London, 2003), pp. 17–69.
7. X. Yang et al., "Quantitative characterization of correlations between casting defects and mechanical strength of Al–7Si–Mg alloy castings," *Materials Science & Technology*, **22**, pp. 561–570 (2006).
8. J. Campbell, "Entrainment defects," *Materials Science & Technology*, **22**(2), pp. 127–145 (2006).
9. J. Knott et al., "Commentaries on 'entrainment defects' by J. Campbell," *Materials Science & Technology*, **22**, pp. 999–1008 (2006).
10. R. Raiszadeh and W.D. Griffiths, "A method to study the history of a double oxide film defect in liquid aluminum alloys," *Metallurgical and Materials Transactions. B*, **37**, pp. 865–871 (2006).
11. J. Mi et al., "entrained oxide films in TiAl castings," *Intermetallics*, **11**, pp. 377–385 (2003).
12. S. D. Felicelli, D. R. Poirier, and P. K. Sung, *Metall. Mater. Trans. B*, **31B**, pp. 1283–1292 (2000).
13. S. D. Felicelli, J. C. Heinrich, and D. R. Poirier, *Int. J. Numer. Meth. Fluids*, **27**, pp. 207–227 (1998).

14. Q. T. Fang and D. A. Granger, *AFS Trans.*, **97**, pp. 989–1000 (1989).
15. L. H. Rhee Wang et al., "Oxide Film and Porosity Defects in Magnesium Alloy AZ91," 2009 TMS Annual Meeting & Exhibition, Shaping Casting: Third International Symposium, San Francisco, California, February 15–19, 2009 (in review).
16. S. D. Felicelli et al., "A model for gas microporosity in aluminum and magnesium alloys," *Metallurgical and Materials Transactions B* (in review).
17. W. D. Griffiths and N. W. Lai, "Double oxide film defects in cast magnesium alloy," *Metallurgical and Materials Transactions A*, **38**, pp. 190–196 (2007).

F. Multi-Material Metallurgical Bond Joining to Steel

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Participants:
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Bruce Cox, Chrysler Corporation; e-mail: bmc8@chrysler.com
Larry Ouimet, General Motors Corporation; e-mail: larry.j.ouimet@GM.com

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Contract No.: DE-FC26-02OR22910

Objectives

- The primary objective of this concept feasibility project is to verify that the proposed technology can achieve a true metallurgical bond between cast aluminum (Al) and steel and between cast magnesium (Mg) and steel. There are no known alternative, economically attractive processes that can achieve a true metallurgical bond.
- The metallurgical bond between Mg and Al will also be assessed.
- Technical hurdles to implementation will be identified for potential follow-on work.

Approach

- The project team will create test criteria and identify potential target applications.
- Test piece castings will be designed for selected inserts that meet the test criteria.
- Dr. Han will develop the process for and manufacture the test castings.
- The cast components will be tested according to the test procedure and analyzed by the team.
- Technical hurdles to implementation will be identified for potential follow-on work.
- Information and data will be distributed to the participating companies.

Accomplishments

- The test criteria team was established with OEM and supplier participants.
- The test criteria team identified potential applications for the technology to be developed for joining Al to steel, Mg to steel, and Al to Mg. Included in the potential components list were the anticipated cast materials and insert descriptions.
- In light of the first potential components list exercise, the team identified the casting materials, and insert materials to be considered for the test castings to be produced by Dr. Han.
- The team established the testing criteria.
- Three casting designs were created to meet all the test criteria established.
- Early stage development has shown that a strong metallurgical bond can be achieved with this technology for steel pins in cast Al.
- Technical hurdles to implementation have been identified for potential follow-on work.

Future Directions

- Remaining test piece castings will be manufactured with selected inserts that meet the test criteria.
- The cast components will be tested according to the test procedure and analyzed by the team.
- The final technical hurdles to implementation list will be completed for potential follow-on work.

Introduction

The pressure to reduce weight and improve fuel economy has resulted in increased numbers of cast Al and Mg components that need to be attached to the existing steel architectures. The joining of these multi-material components requires traditional bolted connections, mechanical locking strategies, or other non-traditional welding processes. These joining solutions result in added costs and potential offsetting mass (bolts, bosses, flanges, etc.) This project proposes to develop and evaluate a new concept in bonding cast Al and Mg components to steel. The new concept creates a metallurgical bond when ultrasound is applied to a steel insert (sheet, tube, rod, etc.) during the casting process without significant alteration to the casting cycle time or process. It is envisioned that the development of this technology could result in cast components with weldable steel inserts that could be joined to today's steel architectures by currently available, economical production processes like spot welding.

The development approach will build upon preliminary work done at Oak Ridge National Laboratory. Test castings will be made with this new technology, tested and evaluated. In addition, technical hurdles to implementation will be identified for potential follow-on work.

Background

The processes for joining multi-material components (Al, Mg, and steel) into vehicle structures often add cost and offset weight saved from the use of the lighter weight materials. Capital costs may be increased to implement nontraditional welding processes, machining processes, fastener assembly stations, associated material handling systems, etc. Operating costs also increase due to these added processes and parts. In addition, some of the mass reduced by using the lighter weight materials is offset by added locking features, bolts, bolt bosses, flanges, and other features.

Recent investigative development at Oak Ridge National Laboratory has shown that it is possible to achieve a metallurgical bond between Al and steel or Mg and steel by applying ultrasound to steel inserts in molds for casting of the lighter metals. The initial work seemed to indicate that there was no significant loss in productivity due to the introduction of the insert or ultrasound. However, significant development and testing is needed to verify these assumptions and identify the risks and opportunities for application of this technology.

Work Completed

Task 1: Establish Team, Confirm Target Applications, and Create/Identify Test Criteria

Approach:

- Establish team
- Define potential applications for the technology to be developed for joining Al to steel and Mg to steel.
- Select an Al and Mg alloy.
- Define metrics of success and attributes of a good bond (physical properties, metallurgical properties, and corrosion performance). Criteria to be considered:
  - Features required for test piece
  - Bond line interface quality
  - Diffusion layer distance
  - Brittleness
  - Raw Strength
  - Key life testing
  - Pull-out/shear
  - Peel
  - Fatigue
  - Porosity
  - Corrosion performance
  - Process parameters (i.e. time to produce metallurgical bond, ultrasonic control and measurement aspects, etc.)
  - Requirements for steel sample preparation, etc.

Deliverables:

- Team established
- Potential application(s) (flanges, tubes, etc.) defined.
- Testing criteria and metrics of success defined.
- Requirements for the casting design and insert(s) defined.

Results:

- The test criteria team was established and functioning with active participation from:
  - Chrysler
  - Ford
  - General Motors
  - Purdue
  - TechKnowledge
- The test criteria team identified potential applications for the technology to be developed for joining Al to steel, Mg to steel, and Al to Mg. Included in the potential components list were the anticipated cast materials and insert descriptions. The potential components list is included in the appendix to this report.
- The team settled on the following testing criteria for analyses of the test castings:
  - Cross sectioning
  - Torsional force
  - Pull or push force (depending on bond to be tested)
  - Die penetrent
  - Stress/strain
  - Peel
- Based upon the work completed in the first task, the team identified the casting materials and insert materials to be considered for the test castings to be produced by Dr. Han.

Casting Material	Insert
Mg AZ91E	Mild steel weldable flange
Al 356	Mild steel weldable flange
Mg AZ91E	Steel rod
Al 356	Steel rod
Mg AZ91E	Al 6061 rod
Mg AZ91E	Al 356 cast material

Task 2: Design Test Casting and Steel Inserts:

Approach:

- Design the test casting and steel insert(s) to satisfy testing criteria establish in Task 1.

Deliverables:

- Casting design completed.
- Insert(s) design completed.

Results:

- The test criteria team identified three casting designs that would achieve all the objectives established in Task 1.

The three designs are:

Design 1

The design 1 is illustrated in Figure 1. An insert will be cast in with a cylindrical casting. The test casting will be tested for shear strength and fatigue. Three combinations of metals will be made: steel insert in Mg casting, steel insert in Al casting, and Al insert in Mg casting. For each combination, 15 samples will be made and shipped to the United States Council for Automotive Research (USCAR) for testing.

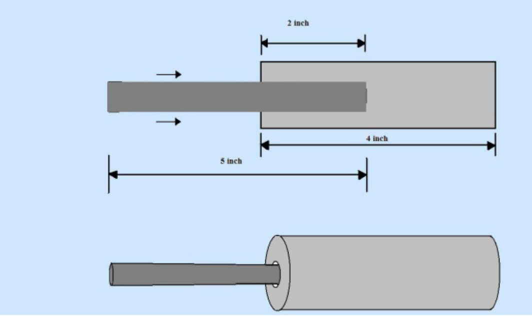

Figure 1. Test Casting Design 1.

Design 2

Design 2 is illustrated in Figure 2. A steel or Al strap will be joined to an Al or Mg disc casting. Testing will be carried out to determine the interfacial strength between the strap and the 2 inch diameter puck. Three combinations of metals will be made: steel strap with Mg casting, steel strap with Al casting, and Al strap with Mg casting. For each combination, 15 samples will be made and shipped to USCAR for testing.

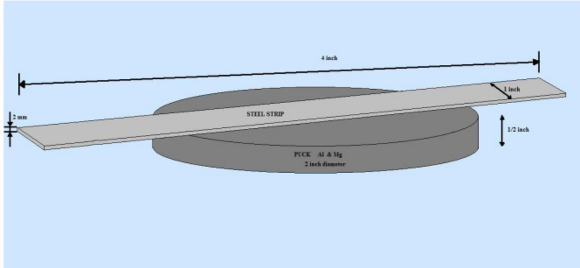

Figure 2. Test Casting Design 2.

Design 3

Design 3 is illustrated in Figure 3. This design will be used to test mi-metal casting. An Al casting (half a disc) will be made in a mold. Molten Mg alloy will then cast to make a disc half Al and half Mg. The joint between the Al half and the Mg half will be tested. 15 specimens will be made and shipped to USCAR for further testing.

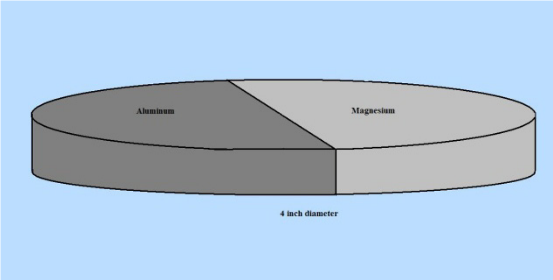

Figure 3. Test Casting Design 3.

Task 3: Develop Process and Make Test Pieces

Approach:

- Prepare mold and ultrasonic tooling (simple molds will be used during this task)
- Procure materials
- Prepare inserts
- Develop the process for manufacturing the test pieces
- Manufacture test pieces
- Document process data

Deliverables:

- Mold and ultrasonic tooling prepared and ready for casting process.
- Samples ready for material and property evaluations.
- Data set captured.

Results:

- Design 1 test castings, steel pin in Al and steel pin in Mg, were manufactured and distributed for testing.
- Design 2 test castings, steel strip on Al, were manufactured and distributed for testing.

Task 4: Test and Evaluate Test Pieces

Approach:

- Test, evaluate, analyze and verify that the new casting/joining process can achieve metallurgical bond between Al to steel and Mg to steel as defined in Task 1. Evaluations will consider physical/ mechanical and metallurgical properties and corrosion performance.

Deliverables:

- Test results and analysis of the capability of this technology to bond multi-material structures.

Results:

- Design 1 test castings, steel pin in Al, were tested by Ford and Casting Technologies Company. Micrographs and physical testing indicated a metallurgical bond was achieved with evidence of tearing of Al during the push out (shear stress) testing. Micrographs indicated a transitional zone between the Al and steel at the joint.
- Design 1 test castings, steel pin in Mg, were tested at Purdue and did not indicate a metallurgical bond was achieved. It was concluded an additional step might be required like pre-coating the steel pin with Al prior to casting into the Mg.

Task 5: Information Dissemination and Reporting:

Approach:

- Identify technical hurdles to implementation
- Disseminate technology to team members

Deliverables:

- Final reports
- Identification of hurdles to implementation

Results:

- Technical hurdles list created and maintained and included in appendix to this report.
- All results distributed to team and maintained on USCAR V-Room secured virtual information site.

Work to be Completed

Task 3: Develop Process and Make Test Pieces

- Complete test castings for:
  - Design 1 steel rod in cast Mg
  - Design 1 Al rod in cast Mg
  - Design 2 steel strip to cast Mg
  - Design 3 cast Al to cast Mg

Task 4: Test and Evaluate Test Pieces

- Complete testing and analyses of all cast test pieces

Task 5: Information Dissemination and Reporting:

- Complete dissemination of all information to team
- Provide final report

Conclusions

Early stage results indicate the concept is a viable means to bond steel to cast Al. The remaining tasks to be completed will determine if similar success can be achieved with Mg to steel and Mg to Al. The team has identified a broad number of potential applications for this technology that could result in weight and cost reductions in the fastening of lightweighting materials to vehicle structures. With the successful development of this technology it is clear that lightweighting materials such as Mg will be enabled for increased usage.

Appendix

Multi-Material Metallurgical Bond Joining to Steel

MMV 704[*]

Potential Component List
March 20, 2008

Interior Components:

Component	Cast Material	Inserts
Steering column support	Magnesium	Cast-in steel nuts and studs
	Aluminum	Cast-in steel nuts and studs
Steering wheel arm	Magnesium AM 50 or 60	Cast-in steel bushings
	Aluminum	Cast-in steel bushings
I/P (cross car beam)	Magnesium AM60	Cast-in steel nuts and studs and steel support structures
Seat structures	Magnesium AM 50 or 60	Cast-in steel nuts and studs and steel support structures
Center consuls	Magnesium AM60	Cast-in steel nuts and studs
Knee bolsters	Magnesium AM60	Cast-in steel nuts and studs
Door handles	Magnesium AZ91D	Cast-in steel nuts and studs

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Potential Component List

Body Components:

Component	Cast Material	Inserts
Roof components	Magnesium AM60/AZ91D	Cast-in nuts and studs
	Aluminum 356	Cast-in nuts and studs
Shot guns	Magnesium AM60	Cast-in nuts and studs and weldable steel flanges
Radiator supports	Magnesium AM60	Weldable steel flanges
	Aluminum 5754	Weldable steel flanges
Door Inners	Magnesium AM60	Cast-in nuts, tapping plates, studs, and weldable steel flanges
	Aluminum 356	Cast-in nuts, tapping plates, studs, and weldable steel flanges
Lift gate inners	Magnesium AM60	Cast-in nuts, tapping plates, studs, and weldable steel flanges
	Aluminum356	Cast-in nuts, tapping plates, studs, and weldable steel flanges
Magnesium front end	Magnesium	Cast-in nuts, tapping plates, studs, weldable steel flanges, and aluminum isolation plugs, plates and flanges
Mirror brackets	Magnesium AM60	Aluminum isolation plugs and flanges

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[*] Denotes project 704 of the Multi-Material Vehicle (MMV) focus area 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. See www.uscar.org.

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Potential Component List

Chassis Components:

Component	Cast Material	Inserts
Sub frames (cradles and Cross members)	Magnesium AM60	Cast-in nuts and tapping plates, and aluminum isolation plugs, plates and flanges
Control arms	Magnesium	Cast-in nuts and tapping plates
Wheels	Magnesium	Hybrid design with aluminum hub area and magnesium tire rim
ABS brackets	Magnesium AZ91D	Aluminum isolation plugs, plates, and flanges
Steering racks	Magnesium AZ91D	Aluminum isolation plugs, plates, and flanges
Steering knuckles	Magnesium AM60	Aluminum isolation plugs, plates, and flanges
Covers	Magnesium AZ91D	Aluminum isolation plugs, plates, and flanges
Boxes	Magnesium AZ91D	Aluminum isolation plugs, plates, and flanges
Brake Pedals	Magnesium AM60	Cast-in nuts and tapping plates

Power Train Components:

Component	Cast Material	Inserts
FEAD	Magnesium AZ91D	Aluminum isolation plugs, plates, flanges and cast-in steel nuts and studs
	Aluminum 380	Cast-in steel nuts and studs
Transfer Cases	Magnesium AZ91D	Aluminum isolation plugs, plates, and flanges
	Aluminum 380	Cast-in steel nuts and studs
Oil Pans	Magnesium AZ91D	Aluminum isolation plugs, plates, and flanges
	Aluminum 380	Cast-in steel nuts and studs
Brackets	Magnesium AZ91D	Aluminum isolation plugs, plates, and flanges
	Aluminum 380	Cast-in steel nuts and studs
Front Covers	Magnesium AZ91D	Aluminum isolation plugs, plates, flanges and cast-in steel nuts and studs
	Aluminum 380	Cast-in steel nuts and studs

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