Final Technical Report

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Principal Investigator:	Jon T. Carter Phone: 249-912-8506 Email: jon.t.carter@gm.com
Team Members:	Meridian Lightweight Technologies Ohio State University
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LIST OF ACRONYMS

AM60 – Mg-based alloy containing approximately 6% Al and 0.4% Mn

AZ91 – Mg-based alloy containing approximately 9% Al and 1% Zn

AT72 – Mg-based alloy containing approximately 7% Al and 2% Sn

ATS721 – Mg-based alloy containing approximately 7% Al, 2% Sn, and 1% Si

CAD – Computer aided design

CAE – Computer aided engineering

CED – Cumulative energy demand

CMM – Coordinate measuring machine

CNC - Computer numerical control

FMVSS - Federal Motor Vehicle Safety Standard

GHG – Greenhouse gases

GPa – Giga Pascals

GWP – Global warming potential

HPDC – High-pressure die casting

IDC - Integrated die casting

LCA – Life cycle analysis

MPa – Mega Pascals

SEM – Scanning electron microscope

SVDC - Super-vacuum die casting

UTS – Ultimate tensile strength

YS – Yield strength (measured in tension)

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SECTION 1: EXECUTIVE SUMMARY

The purpose of this "Development of Integrated Die Casting Process for Large Thin-Wall Magnesium Applications" project, hereinafter referred to as the IDC project was to develop a process and product which would utilize magnesium die casting and result in energy savings when compared to the baseline steel product. The specific product chosen was a side door inner panel for a mid-size car. The scope of the project included: re-design of major structural parts of the door, design and build of the tooling required to make the parts, making of parts, assembly of doors, and testing (both physical and simulation) of doors. Additional work was done on alloy development, vacuum die casting, and overcasting, all in order to improve the performance of the doors and reduce cost.

The project achieved the following objectives:

1. Demonstrated ability to design a large thin-wall magnesium die casting.
2. Demonstrated ability to manufacture a large thin-wall magnesium die casting in AM60 alloy.

3. Tested via simulations and/or physical tests the mechanical behavior and corrosion behavior of magnesium die castings and/or lightweight experimental automotive side doors which incorporate a large, thin-wall, powder coated, magnesium die casting. Under some load cases, the results revealed cracking of the casting, which can be addressed with re-design and better material models for CAE analysis. No corrosion of the magnesium panel was observed.
4. Using life cycle analysis models, compared the energy consumption and global warming potential of the lightweight door with those of a conventional steel door, both during manufacture and in service. Compared to a steel door, the lightweight door requires more energy to manufacture but less energy during operation (i.e., fuel consumption when driving vehicle). Similarly, compared to a steel door, the lightweight door has higher global warming potential (GWP) during manufacture, but lower GWP during operation.
5. Compared the conventional magnesium die casting process with the "super-vacuum" die casting process. Results achieved with cast tensile bars suggest some improvement in tensile properties with vacuum casting. Plant trials with large castings revealed cavity fill issues attributed to cooling and partial solidification of metal in the shot sleeve while waiting for vacuum to be established in the die cavity.
6. Developed age-hardenable Mg-based alloys as potential alternatives to the AM60 and AZ91 alloys typically used in automotive applications. Mg-7%Al-based alloys having Sn or Sn+Si additions exhibited significant age hardening, but more work is needed to demonstrate significant improvement in tensile properties. Corrosion behavior of these alloys is between those of AM60 and AZ91 alloys.
7. Evaluated the die casting of magnesium directly onto either steel or aluminum tubes as a potential process to make large lightweight subassemblies. Samples were free of gross defects, but additional work is needed to increase the interfacial shear strength.

Overall, the project demonstrated that an automotive door-in-white design incorporating a die cast magnesium inner panel and a stamped aluminum outer panel can achieve approximately 50% mass reduction compared to the stamped steel baseline door-in-white. This leads to reduced energy consumption when driving the vehicle, which should more than offset the increased embedded energy of manufacture associated with the lighter metals. However, additional design work would be needed in order to meet the mechanical performance required of a door. Development of high-strength, high-ductility magnesium alloy castings would help make this technology more attractive for potential use in the side doors on automobiles. Also, increased use of <u>recycled</u> magnesium and aluminum would reduce the embedded energy and greenhouse gas emissions associated with the manufacture of this type of lightweight door.

Commercialization planning of the type of lightweight door technology addressed in this project would be contingent upon the doors meeting all technical performance requirements of the car maker. The specific lightweight door developed in this project didn't meet some of those requirements, but a preliminary business case study was conducted anyhow. This study considered the ratio of cost increase to mass decrease when the lightweight door is compared to a baseline steel door. The ratio was found to be in an acceptable range for some vehicle programs, especially if the number of such vehicles to be produced is equal to or slightly less than the estimated 250,000-

shot life of the die set. This would allow for the investment in the dies to be spread across many parts and thereby help minimize the cost increase. No additional commercialization planning is recommended until after design improvements enable the door to meet all performance requirements.

SECTION 2: INTRODUCTION

(i) The technology addressed in this project is high-pressure die casting (HPDC) of magnesium alloys for structural applications, and specifically for an experimental, lightweight, automotive side-door inner panel. In the HPDC process, a measured amount of molten alloy is rapidly forced into a precision steel mold, solidified, then ejected. The mold then gets automatically cleaned of debris, sprayed with a die release agent, then closed up to prepare for the next shot of incoming molten metal. The process may produce castings having thin walls, many geometric features, smooth surface finish, and good dimensional accuracy, with a cycle time on the order of two minutes for large castings. A variant of this process includes the use of vacuum systems to remove air and other gases from the mold cavity just prior to injection of the molten metal, thereby reducing the amount of gas porosity in the resulting casting and thus increasing its mechanical properties. In another variant, called overcasting, metal inserts are placed on precise locators within the mold just prior to the mold closing. These get partially surrounded by the molten metal and eventually become highly functional portions of the final part, such as iron cylinder liners in HPDC aluminum engine blocks.

(ii) The typical structural portion of a side door inner sub-assembly on a car comprises several pieces of steel sheet which are stamped into shapes, then joined together by spot welding. In areas which carry higher loads, reinforcements are added locally to help stiffen and strengthen the relatively thin sheet metal. Additional pieces may be added to, for example, provide a guide channel for the window glass, or an attachment point for a bracket. As a result, this type of design utilizes metal which has undergone extensive rolling operations in order to make the starting sheet, then through various stamping, assembling, and welding operations in order to make the inner panel sub-assembly. A potentially attractive alternative approach is to simply cast the inner panel as a single piece in a precision die, albeit with some re-design to accommodate the casting process. HPDC of magnesium or aluminum alloys are likely candidate processes, and are already used in various automotive body applications including liftgate inner panels, instrument panel beams, radiator supports, and portions of side door inner panels. HPDC of magnesium complete ("full header") side door inner panels, including the portion above the top of the window glass, would simplify the assembly complexity of inner panels by enabling local increases in wall thickness in highly loaded areas, ribbing for increased stiffness, and cast-in features for brackets and attachment points. By avoiding the sheet rolling and welding processes, the Mg HPDC approach would avoid certain embedded energies of manufacture. And the reduced mass of the Mg door (due largely to Mg having a lower density than steel), compared to a steel door, on a car would result in increased fuel economy during the "use" phase of the door life cycle. This technology and type of application could be enhanced by (a) alloy development to increase strength and ductility, (b) super-vacuum die casting to help reduce porosity in the casting and thus improve mechanical properties, and (c) overcasting Mg onto Al inserts in the mold, thereby either eliminating the need for a subsequent joining step or providing a functional attachment point.

(iii) Preliminary models assumed that a 50% mass reduction could be achieved in a door based on an HPDC Mg inner panel rather than stamped steel. These early models predicted (a) 50% (0.1 megaBtu per door) less embodied energy than baseline sheet steel door, (b) 7.4 kg/yr/vehicle CO_2 reduction through improved vehicle fuel economy, and (c) $15 per door manufacturing cost savings. If these early predictions are correct, and if this technology were to be implemented on the front doors of 10% of the North American annual sales volume of 17 million vehicles, the results would be (a) 340 gigaBtu/year less embodied energy of manufacture, (b) 12.6 million kg/year CO_2 reduction through improved vehicle fuel economy, and (c) $51 million/year manufacturing cost savings.

(iv) Commercialization of this type of new technology application would first require demonstration of successful completion of door tests for durability, impact, corrosion, paint appearance, noise, etc., and compatibility with existing manufacturing processes, especially automotive paint shop processes. Then, a type of cost vs. benefit analysis would be done in which the "cost" is the cost difference between Mg door and steel door implementations, and the "benefit" is the mass difference the two doors. (Typically, there is a cost penalty when changing structural materials in order to reduce vehicle mass. Depending on total part production volume and the cost and life of the dies, the fixed cost of the dies may be a significant portion of the part cost.) The size of the ratio of delta cost to delta mass, expressed in $/kg-saved, will help determine which vehicle models would be most likely use the new type of door. And depending on the proposed region (North America, Asia, Europe, etc.) for implementation, there would likely be an assessment of the perceived long-term availability of raw materials, as well as the number of local suppliers who are able to make the die casting.

SECTION 3: BACKGROUND

Modern magnesium die casting alloys and processes enable the cost-effective, high-volume production of structural parts for various end uses, including power tools, portable electronic devices, and automobiles [1-3]. The typically-cited advantages of such parts include low mass, part consolidation, fine details and geometric features, good machinability, good vibration damping, good electrical conductivity and EMI shielding. Potential disadvantages include a low modulus of elasticity (compared to aluminum or steel) and a tendency for aqueous corrosion, especially if in contact with another metal or carbon fiber. Generally speaking, these issues can be managed by careful design.

Most of the use of magnesium in series production automobiles is in the form of high-pressure die castings, but some recent applications of sheet will be mentioned here for completeness. These use the AZ type of magnesium alloy, which typically contains 3% Al, 1% Zn, and 0.3% Mn, all by weight. General Motors used magnesium sheet for the decklid inner panel on some Cadillac SLS sedans [4]. These panels were formed by a hot gas blow forming process near 500 ^{o}C, similar to how most of the aluminum counterpart panels were made [5]. This change of material resulted in approximately 30% (1.2 kg) mass reduction, but did require an additional manufacturing step (i.e., powdercoating of the Mg panel prior to decklid assembly) to prevent aqueous corrosion in service. Renault Samsung Motors uses a magnesium sheet panel in the SM7 sedan between the back of the rear seat and the trunk [6]. Judging from the published photograph, this panel is much flatter than the Cadillac decklid panel, and therefore might be formable by warm stamping, which is much faster than hot gas blow forming. Its bare appearance in a painted car suggests that it is bolted to the body during General Assembly, which comes after Body Shop and Paint Shop in the automotive assembly process. It also suggests that the operating environment (i.e., interior of car and off the floor) is dry enough that an anti-corrosion coating isn't needed. Porsche uses magnesium sheet in the roof panel on their 911 GT3 RS performance car [7]. The associated mass reduction in the roof location lowers the car's center of gravity. Because this is a highly visible exterior panel on a premium vehicle, the manufacturing steps must be done carefully in order to achieve the desired paint appearance on the finished car.

Experimental work has also been done with warm stamping of an automotive side door inner panel using the ZEK100-type of magnesium sheet alloy, which contains approximately 1% Zn, 0.2% Nd, and 0.2% Zr [8]. Due to its composition and thermomechanical processing, this alloy has lower strength and weaker crystallographic texture than AZ31 sheet, and is more amenable to stamping at low temperatures (i.e., below 260 ^{o}C). Such relatively low forming temperatures are attractive because they allow for use of conventional forming lubricants, which are easier to remove than are, for instance, the boron nitride based lubricants which are used in 500 ^{o}C forming.

Die cast magnesium inner panels have been and are being used in both side doors and rear liftgates on both low-volume and high-volume vehicles. The AM60 and AM50 (6% or 5%Al, plus 0.4%Mn) alloys are used rather than the higher strength AZ91 (9%Al-1%Zn) due to their greater ductility and crash energy management. In the early 2000s, Mercedes-Benz used die cast magnesium inner panels for the headerless side doors on SL and CL models. These inners had several stamped aluminum reinforcements which added complexity, but presumably were required in order to meet performance specifications. A 2005 paper [9] reported that careful design could eliminate the need for such reinforcements in both full-headered and headerless doors, and supporting experimental results were presented for the production-intent headerless design. Later work by another car maker led to the use of die cast magnesium for the upper portion of door inner panels, and die cast aluminum for the lower portion [10].

Die cast magnesium liftgate inner panels are used in the low-volume Lincoln MKT crossover vehicle [11], and more recently in the high-volume Chrysler Pacifica mini van [12]. As with the side door inners, these panels offer reduced mass, part consolidation, and styling options which might not be available with stamped aluminum due to restrictions on draw depth and corner radii.

Most automotive magnesium die castings utilize either the AM60/AM50 or AZ91 alloys in the as-cast (i.e., not heat treated) condition, and are made by the conventional high pressure die casting process. The resulting tensile properties are 125 MPa YS and 10% elongation at fracture for AM50, and 160 MPa and 3% for AZ91 [2]. Work on AT72 (7% Al and 2% Sn) has shown that its tensile properties can be improved by using a "super vacuum" HPDC process rather than conventional, and also by heat treatment. ("Super vacuum" means that the die cavity is evacuated to less than 50 mbar pressure just prior to the molten metal being injected. Heat treatments which include solutionizing generally aren't done on conventional HPDC parts because gas porosity near the surface expands at the 400+ ^{o}C solutionizing temperature, thereby creating "blisters" on the surface. Super vacuum largely eliminates the chance of blistering, and thereby allows for possible use of alloys which require a T4 or T6 heat treatment to achieve the desired tensile properties.) Specifically, the YS and % elongation are increased from 92 and 5.3 with conventional HPDC to 143 and 6.4 with super vacuum HPDC. The authors attribute the improvements to finer grain size and reduced porosity. T4 solution heat treatment of the super-vacuum castings reduces the YS to 88, but increases % elongation to 12. T6 heat treatments result in 107-118 MPa and 4.5-6.6 % elongation, depending on the aging temperature. TEM revealed fine Al-rich and Sn-rich precipitates which are believed to harden the T6 samples. The results of this work suggest possible benefits of super vacuum HPDC, heat treatment, and alternative alloys for use in structural magnesium castings.

The subject of the current project is the energy and greenhouse gases (GHG) associated with side doors on cars and light trucks, and particularly how those are impacted by the choice of the structural metals and manufacturing processes. More specifically, a structure made by welding together of several steel stampings vs. one made by HPDC of a single magnesium panel. The project addresses energy consumption and GHG emissions during both the manufacture and use phases of the product life. It aims to minimize both for the lightweight (magnesium + aluminum) door by minimizing the mass of each of the light metals used in the product design. It doesn't directly address important factors of manufacturing processes, such as primary metal production processes, casting yield, engineered scrap in sheet stamping, etc.

The project team comprises members who are highly trained and have many years of practical experience in relevant subject areas. These areas include mechanical design and structural analysis of doors, magnesium die casting for automotive applications, business case analysis, project management, alloy and process development, mechanical testing, and corrosion testing. Almost all are college educated in technical fields, and many hold graduate degrees. Two are world-renowned researchers in the area of light-metals, especially for automotive applications. Recent production implementations of magnesium by team members includes: die cast liftgate inner panel for Chrysler Pacifica, die cast radiator support for Ford F150 pickup truck, die cast engine cradle for Chevrolet Corvette, and hot blow-formed sheet decklid inner panel for Cadillac SLS.

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SECTION 4: COMPARISON OF ACCOMPLISHMENTS WITH GOALS

The goal of the project was to demonstrate the feasibility of replacing a large steel panel in a structural automotive application with a thin-wall magnesium die casting. The new structure was to meet all functional requirements such as stiffness, strength, and corrosion resistance, and have reduced embedded energy of manufacturing compared to the steel baseline. The IDC innovation was to address the following key issues that have prevented the pervasive use of castings in large parts traditionally made from stamped steel: 1) achieve thin-wall capability (of 1.5-2 mm) in magnesium casting applications (where current state of the art for large thin-walled magnesium castings is 3-4mm) by using advanced super-vacuum die casting (SVDC) technology and a new high-strength magnesium alloy, AT72 (Mg-7%Al-2%Sn), both for mass efficiency; and 2) increase part integration potential well beyond what is possible with conventional die casting processes by consolidating multi-piece industrial structures into large single-piece castings using overcasting technology and advanced process simulation tools.

1. The project did achieve the goal of 2 mm wall thickness in different regions of the door inner panel casting. Thicker walls and/or ribs were used where needed to achieve stiffness and strength targets, thereby increasing parts integration by eliminating the need for separate structural reinforcement pieces.
2. The project achieved mass reduction of approximately 50% with the lightweight door-in-white structure. However, the experimental doors didn’t meet some of requirements of side doors during mechanical testing.
3. The project didn’t achieve 50% reduction in embedded energy, but did show 17-38% reduction in cumulative energy demand (CED) associated with the lightweight door. (CED includes both the embedded energy of manufacture and the energy consumed during 200,000 mile (321,800 km) of driving.)

4. The project demonstrated super-vacuum die casting of magnesium alloys, in both large panels and in small tensile bars. No great benefit was attributed to the use of super vacuum in the project, but further work, such as heating of the shot sleeve on the die casting machine, is suggested.
5. New alloys, including ATS721 (Mg-7%Al-2%Sn-0.75%Si), which can be age hardened, were developed and die cast into tensile bars. Compared to AM60 alloy, they exhibited higher strength but lower ductility. The large door panels were cast only in AM60 alloy. It was intended to also cast door panels using a commercially available variant of AM60 alloy which is made with a CaO addition, and has higher strength and ductility than AM60. But that work did not get done due to unavailability of time for experimental work on the large die casting machines, that were too busy making production parts.
6. Overcasting of magnesium onto steel tubes and aluminum tubes was demonstrated for different diameter tubes and different casting wall thicknesses. The resulting "subassemblies" were free of gross defects. Additional work would be needed to increase the interfacial shear strength. Overcasting wasn't tried with the large panel casting due the anticipated increase in cycle time associated with placing small stampings in the casting die, as well as difficulties in securing the stampings in the die and also in preventing liquid metal from leaking around the stampings into critical areas.

SECTION 5: SUMMARY OF PROJECT ACTIVITIES

The summary of project activities is broken down into the following list of key activities. It provides a high-level overview reflecting principal accomplishments and inter-relationships between the activities.

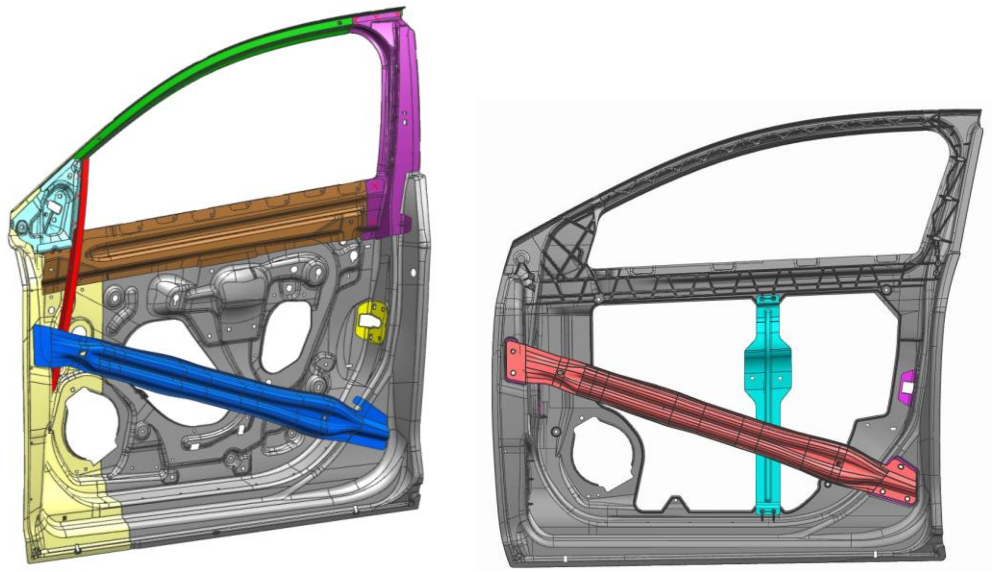
1. Door Selection and Design
2. Die Design for Door Inner Panel and Casting of Inner Panels
3. Checkload Durability
4. Quasi-Static Side Pole Intrusion (FMVSS 214)
5. Life Cycle Analysis
6. Corrosion
7. Overcasting
8. Alloy Development
9. Super-vacuum Die Casting and Tensile Properties

5.1 Door Selection and Design

A goal of the project was to "develop an integrated die casting process for large, thin-walled structural magnesium alloy panels that will reduce process steps, materials usage, and part count, thereby reducing the embedded energy in the manufacturing". The generic type of panel chosen was a car side door inner panel, which poses technological challenges for various reasons:

1. Side door inner panels are large (approximately 1.2 x 1.2 x 0.2 m) and complex structures with mounting points for numerous other components, including reinforcements, latch, hinge, window regulator, window guides, mirror, and others.
2. Side doors are subject to loading, sometimes abusive, every time the car gets driven.
3. Regions within side doors can get wet from rain or other water that runs down the window glass, and therefore may corrode if not managed properly.

The specific type of door inner panel chosen was the "full header" variety, which means that the portion above the top of the window opening is common to the portion below that opening, rather than being a piece which is made separately and applied later. This choice meant that design of the panel and the die would have to enable molten metal flow for long distances to fill all corners of the panel before solidifying. The specific door design chosen as the baseline against which the project's "magnesium door" would be compared was the front left (driver's) door for the Buick LaCrosse midsize sedan which was built in model years 2010-2016. This was a typical all-sheet-steel welded design. The major structural pieces of this door are shown schematically in Figure 1a. The project team designed the magnesium door structure shown schematically in Figure 1b to fit onto the LaCrosse body and also to make use of several carryover parts, such as the anti-intrusion beam, window glass, latch, and others. Because the inner panel is cast, it was possible to integrate the function of six of the stamped reinforcements shown in Figure 2 into the die cast inner panel shown in Figure 3. However, three new stamped aluminum pieces were added to isolate the steel anti-intrusion beam and the steel checklink body from the coated magnesium inner panel in order to reduce the chance of galvanic corrosion. This very conservative approach to corrosion mitigation lowered the part count reduction to three. Additional work would be required to determine if the isolators are really needed, or if the powdercoat applied to the casting is sufficient to mitigate magnesium corrosion. Also, in order to make room for the die casting gates and runners, much of the below-beltline metal was eliminated in the magnesium design compared to the steel design. This meant that additional bracketry was needed to attach the production window regulator mechanism to the door inner panel. These four pieces were stamped in aluminum sheet and blind riveted to the powdercoated inner panel, as shown in Figure 4a, and led to a net increase of one component for the overall assembly. Future designs could avoid the need for such bracketry by using the "integral channel regulator" concept (US Patent Application 20080289259 A1) which combines the regulator with the glass run channels and moves the attachment points forward and aft far enough to allow for direct connection to the inner panel. The masses of the components that make up the "door-in-white" (DIW) structures are compared in Table 1, indicating a 46% mass savings for the magnesium design.



(a) **(b)**

Figure 1: Major structural pieces of a (a) stamped steel welded door structure and a (b) die cast magnesium door design. Non-magnesium parts shown in (b) include the carry-over steel intrusion beam (orange), the aluminum pull-handle support (teal) and aluminum isolators (lavender). (The outer panels and outer beltline reinforcements are omitted from these figures for clarity. The stamped aluminum window regulator bracketry and forward glass run channel required on the magnesium door are omitted here also.) (Copyright 2015 by International Magnesium Association. Used with permission.)

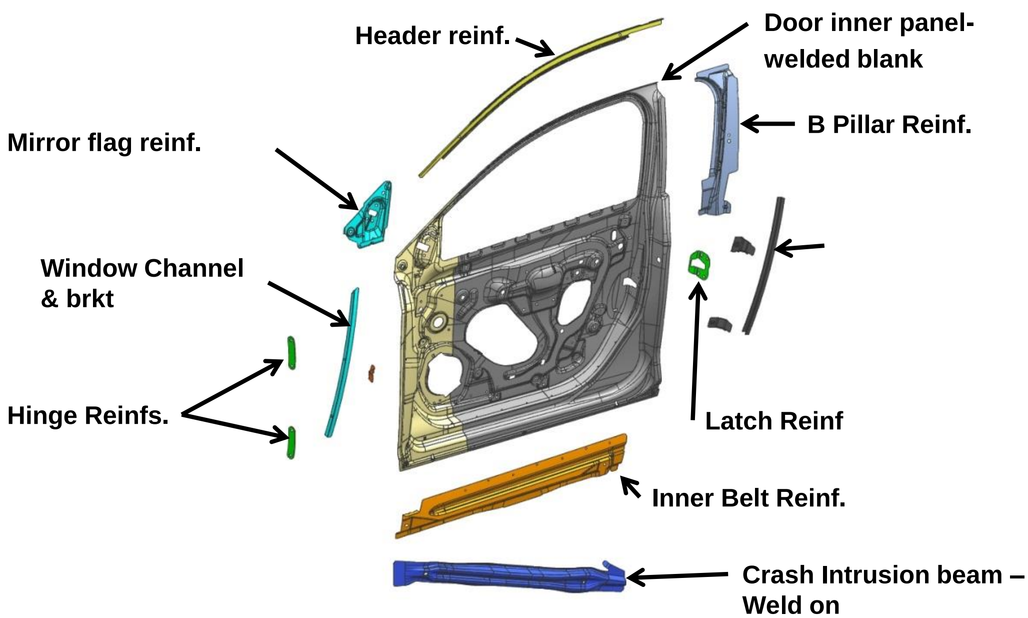


Figure 2: Exploded view of steel door shown in Figure 1a.

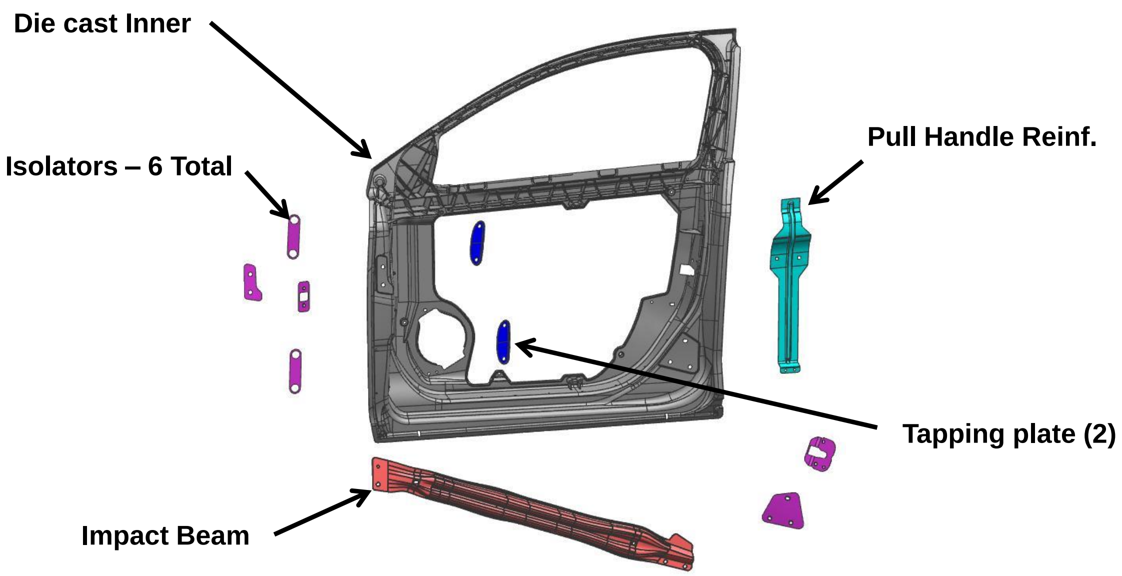


Figure 3: Exploded view of magnesium door shown in Figure 1b.

(a) **(b)**

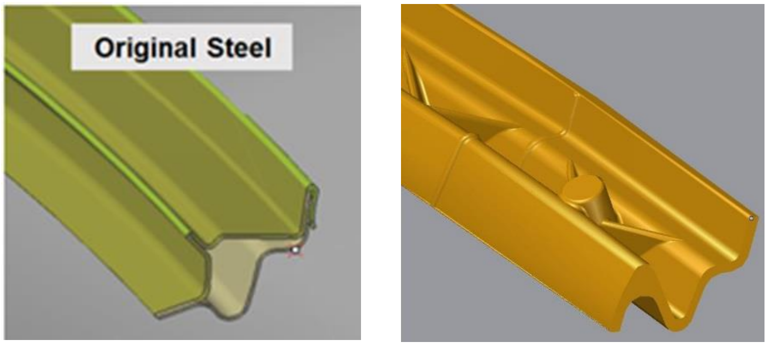
Figure 4: Photograph of magnesium door structure (a) before and (b) after ecoating. The stamped aluminum window regulator bracketry is shown highlighted with red arrows in (a). The magnesium casting appears black in (a) because it was powdercoated prior to attachment of the bare aluminum stampings and the steel hinges.

Table 1: Mass of components in steel and magnesium doors-in-white, kg.

Component	**Steel door**	**Magnesium door**
Inner Panel	7.92	4.05
Outer Panel	5.01	2.72 (aluminum)
Beam/reinf./isolators	4.43	1.84 (steel beam)
Outer Belt Reinf.	0.65	0.37 (aluminum)
Pull Handle Reinf.	0.0	0.23 (aluminum)
Regulator bracketry	0.0	0.272 (aluminum)
Fasteners	0.0	0.21
Total	18.01 kg	9.69 kg

One of the challenging areas of the inner panel to design was the "header", which is the portion along the top edge of the window opening, shown in Figures 5a and 5b. This portion has certain stiffness requirements that must be met in order for the door seals to remain properly compressed during driving at highway speeds, and thereby keep noise, rain, and dust from entering the passenger cabin. This stiffness requirement was readily achieved in the baseline door due to the high elastic modulus of the material (steel), and the high bending stiffness of the closed section created by welding a header reinforcement to the inner panel. The lower modulus of magnesium (44 vs. 210 GPa) and the open-section requirement of the die casting process demanded creative design work. This work resulted in the "S" shaped header cross section shown in Figure 5d, which achieved the header stiffness target with acceptable mass.

(a) (b)



(c) (d)

Figure 5: Graphics showing the header portion of the (a) steel and (b) magnesium door structures, and sections through the headers in (c) steel and (d) magnesium. (Copyright 2015 by International Magnesium Association. Used with permission.)

The joining methods used in the magnesium door were different from the spot welding that is used on steel doors. This is necessary because of the mixed-metal (Mg/Al/steel) nature of the joints and the fact that the Mg inner panel is fully powdercoated (for corrosion mitigation) prior to attachment of any components. Threaded fasteners and blind break-stem rivets were used at various locations on the door-in-white assembly. Two typical bolted-joint designs are shown in Figure 6. Aluminum isolators like the one shown in Figure 6a were used to help reduce the chance of galvanic corrosion of the Mg inner panel near any steel pieces. They had an adhesive applied to help hold them to the inner panel until the through-bolts were installed. An adhesive that expands (permanently) during the ecoat baking step was used in order to completely fill the gaps between isolators and coated inner panel, and thereby help prevent water from getting into the gaps, which would otherwise promote corrosion. The aluminum tapping plate was blind-riveted to the inner panel during the building of these experimental doors. In actual serial production of doors, friction stir spot welding may be a better way to make this joint (whose purpose is to hold the tapping plate to the inner until the bolts are installed). Bolted joints like that shown in Figure 6b were used at both ends of the aluminum outer beltline reinforcement and both ends of the aluminum pull handle reinforcement. They used commercially available thread-forming steel screws and cored holes in the magnesium casting. The cored holes were enabled by making the hole centerlines parallel to the opening direction of the casting dies, eliminating the need for machining locally.

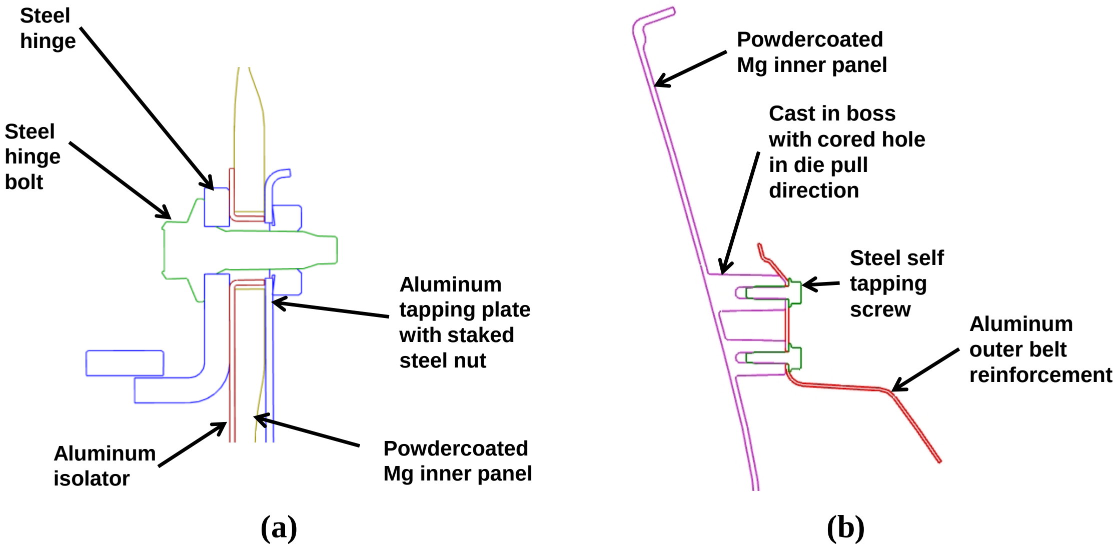


Figure 6: Graphics showing cross sections through bolted-joint designs for attaching (a) steel hinge and (b) aluminum reinforcement to the powdercoated magnesium inner panel. (Copyright 2015 by International Magnesium Association. Used with permission.)

Computer-aided engineering (CAE) was used in design of the lightweight door for various load cases, including checkload durability and side pole impact. This CAE work helped identify high stress regions and thereby allowed for design changes that would reduce those stresses and the potential for deformation and fracture. Checkload durability testing (both physical and simulation) involves having the door on a body in the full-open position, then repeatedly applying loads that try to force the door open further. This additional opening is resisted by a checklink mechanism that spans the gap between the door inner panel and the car body, approximately midway between the two hinges. This leads to the type of stress contours in the door inner panel shown in Figure 7. The high-stress regions identified by simulations were modified by ribbing and increasing wall thicknesses in order to reduce these stresses as the design evolved.

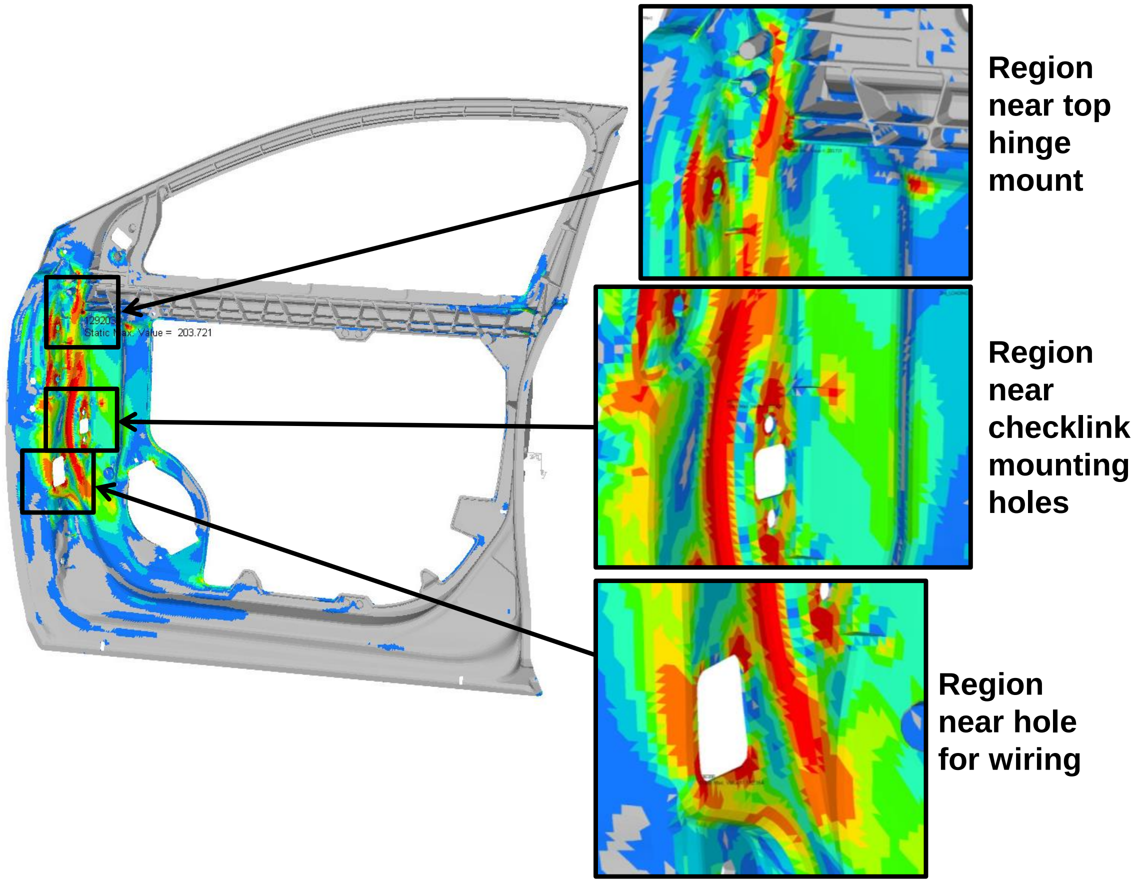


Figure 7: Graphic showing CAE stress contours in door inner panel during abusive loading (500 N) in checkload durability test. High stress areas are shown in red, and they tend to be located around bolt holes, at the corners of rectangular holes, and in the transition region between where the checklink attaches and where the hinges attach. Ribbing and wall thickness changes were made to reduce these stresses.

CAE was also used to compare the predicted responses of the steel and magnesium doors to a dynamic side pole intrusion. During this test a rigid pole impacts the door as prescribed by Federal Motor Vehicle Safety Standard 214 (FMVSS 214) and the resulting loads, stresses, and strains are computed using the CAE material cards for all materials involved. The force vs. pole intrusion curves for the two doors are shown in Figure 8 and indicate higher average forces for the magnesium door, and similar peak forces for the steel and magnesium doors. The resulting deformations of the doors are compared in Figure 9, and the highest strain regions in the magnesium inner panel are circled in Figure 9b. These regions are the forward mount for the beltline reinforcement, the aft mount of the anti-intrusion beam, and the lower portion of the panel near pole contact. The simulation predicted some cracking at these locations if the fracture criterion used was 6% effective plastic strain (EPS), which some consider too conservative for die cast AM60 alloy. If, instead, a 12% EPS fracture criterion is used, then cracking is predicted only at the lower portion of the panel near pole contact.

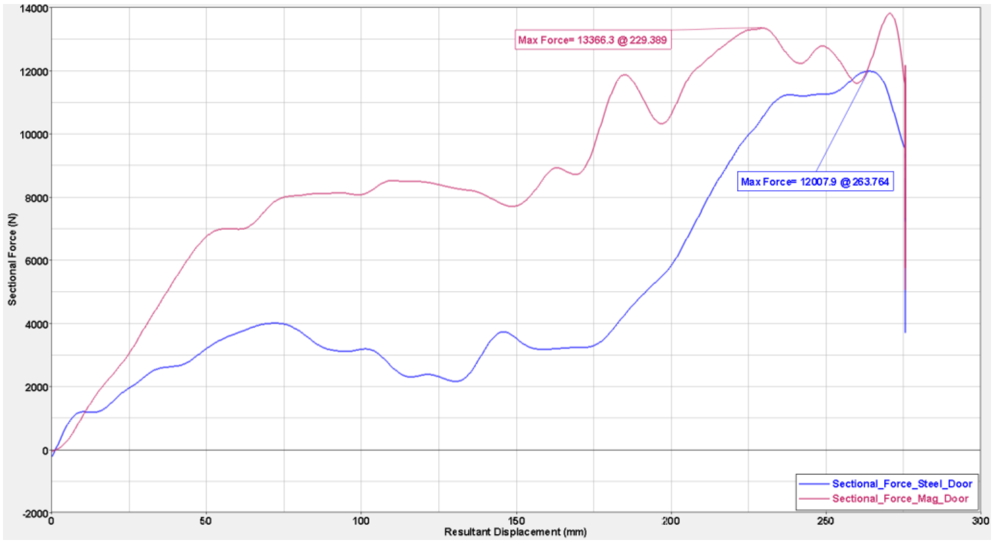
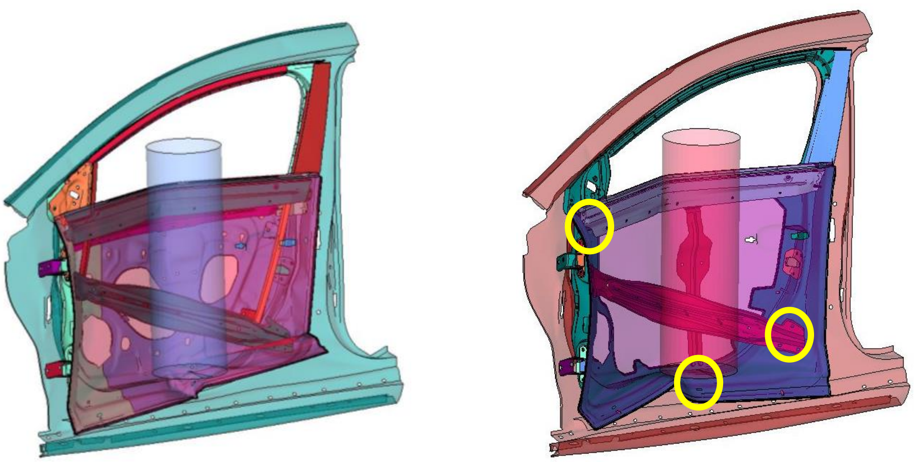


Figure 8: Chart of force vs. displacement (pole intrusion) for simulated side pole intrusions for the steel (bottom, blue curve) and magnesium (top, red curve) doors.

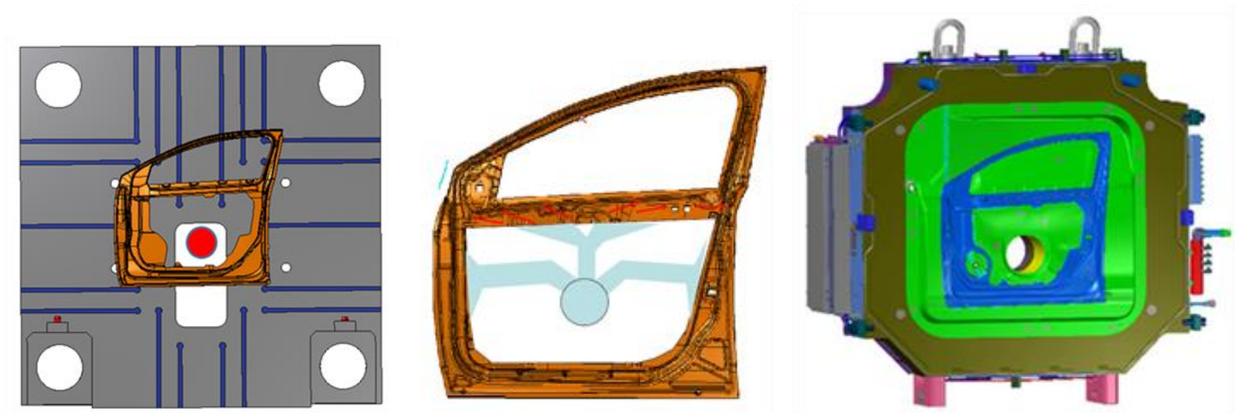


(a) **(b)**

Figure 9: Graphics showing simulated response of (a) steel and (b) magnesium doors to dynamic rigid short pole intrusion of 275 mm during a 20 mph (32 kph) side impact. The yellow circles in (b) mark the areas of highest strain in the inner panel.

5.2 Die Design for Door Inner Panel and Casting of Inner Panels

A feasibility study was first conducted to determine the tool layout based on some critical aspects such as die casting machine tonnage, projected area, basic clearances to tie bars, shot positions and gating. A 3200T die casting machine was selected. Due to the overall size and shape of the casting, standard tool design practices were not feasible. Therefore, the gating was designed in the inner panel region, below the beltline of the door, as shown by the red shot sleeve in Figure 10a and the hole in Figure 10c. For such purpose, the casting geometry was modified to allow for optimal gating. Even with this modification, there was a long metal-flow distance from the shot sleeve to the aft upper corner of the door panel. By careful design of gating, venting, and die thermal profile, complete filling of this thin panel was achieved.



(a) **(b)** **(c)**

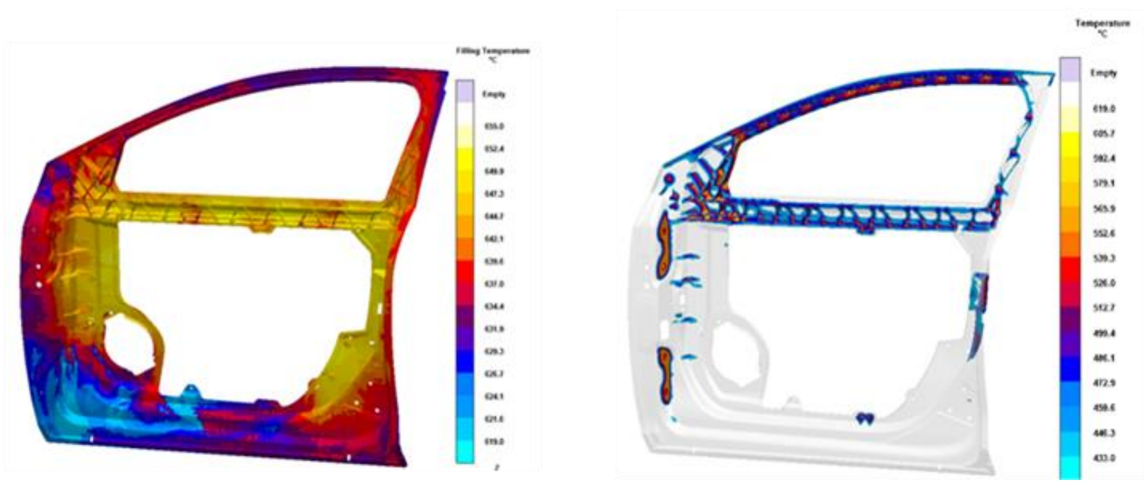
Figure 10. (a) Final die layout with inner panel removed to allow for optimal gating. (b) Center gating concept. (c) Cover die model. (Copyright 2015 by International Magnesium Association. Used with permission.)

Extensive filling and solidification simulation studies were conducted throughout the whole tool design and manufacturing process. The runner, gating, overflow and venting/vacuum systems were optimized to ensure good metal flow characteristics throughout the castings, especially in the critical locations. Some initial simulation results are shown in Figure 11.

In order to better control the filling and solidification process, the tool was designed with special internal heating and cooling. Several different zones were established over the entire casting based on simulation studies. These zones were designed to help optimize the filling process to achieve the minimum wall thicknesses desired by design as well as to manage the heat load during solidification. They are controlled individually using thermocouples embedded in the die at strategic locations and integrated into the casting cell PLC for continuous monitoring and control. This thermal control enabled the adjustment of the heating and cooling of the die based on both filling and solidification related heat loads. Additionally, the die was designed and built with the necessary seals, valves, and vacuum system to allow for thorough removal of air and other gases from the die cavity prior to injection of molten metal. In summary, the use of modern design and simulation tools has enabled the design of the major automotive side-door inner panel shown in Figure 12, plus the die-casting dies and process parameters for manufacturing.

Three multi-day casting trials were run using the door die and AM60 alloy. Most of the castings were made without vacuum, but vacuum was included in the third trial. Slight modifications to the die were made between trials to ensure optimum filling and also to accommodate changes in panel design, such as larger radii and thicker walls in certain areas. These trials generated the panels required by the project for door building and testing. Panels were CNC machined to provide the numerous holes required for mounting hinges, latch, weatherstrip, etc., which could not be cast in. Dimensional checking of castings was done using CMM, and although the deviation from the CAD model was greater than would be required of a production part, it was considered typical for a part of this size at this stage of process development.

Utilization of super-vacuum was found to be detrimental to the casting of inner panels, specifically in terms of die filling. This was attributed to cooling and partial solidification of molten metal in the shot sleeve during the time the die cavity is being evacuated. (During vacuum die casting the valve between the vacuum reservoir tank and the die cavity can be opened only after metal has been poured into the shot sleeve and the plunger tip has moved past the pour hole. Otherwise, the vacuum system will just pull ambient air through the open pour hole and through the die. After the plunger tip passes the pour hole and the vacuum valve is opened, some additional time is required to evacuate the cavity before the plunger may be accelerated to push the metal into the cavity. It is during this “wait” time that partial solidification occurs in the shot sleeve.) This cooler metal didn’t fill the cavity as well as the more molten metal did during non-vacuum casting. Process parameters were changed to improve die filling, but a change to the equipment would be preferred to achieve a more robust process. One possible solution is to add electrical heating to the shot sleeve in order to reduce the amount of cooling that occurs while the cavity is being evacuated.



(a) (b)

Figure 11. Initial results from 1st gating design: (a) metal temperature at the end of filling. (b) metal temperature during solidification.

Figure 12: Die cast AM60 magnesium door inner panel after trimming, machining, and powdercoating.

5.3 Checkload Durability

One experimental lightweight door was mounted on a car body, then subjected to "checkload durability testing" for a total of 45,000 cycles. In this test the door is placed in a wide open position, then forced farther open by a load applied near the latch by a pneumatic actuator, as shown in Figure 13. The first two cycles involve a 500 N load, then all subsequent cycles use a 235 N load. This test stresses the forward face of the door inner panel, including the area around the checklink mechanism (whose purpose is to prevent the door from opening too far in case of a wind gust, for example.)

The door maintained its shape, functionality, and quietness of operation throughout 45,000 cycles. However, some cracking was noticed in the magnesium inner panel as early as 21,000 cycles into the test. These cracks occur at/near certain geometric features which are presumed to act as stress concentrators, including a drilled hole, a reinforcing rib, and the edge of the relatively thick hinge mounting pad. They can be avoided by modifying the design of the inner panel in these areas.

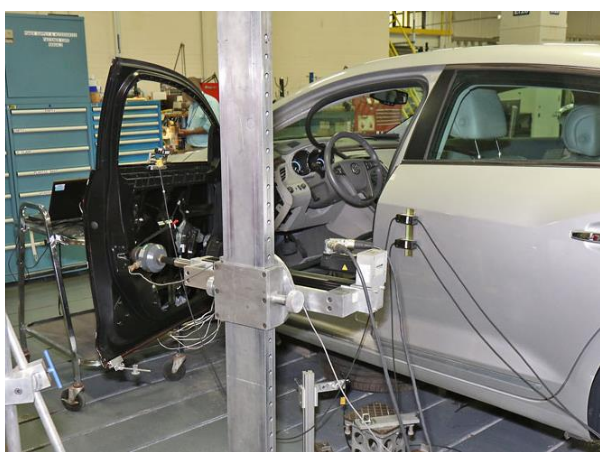


Figure 13. (a) Photograph of an experimental Mg door (black) on a Buick LaCrosse car, together with apparatus to repeatedly push the door in a wide open position with 235 N of force.

5.4 Quasi-Static Side Pole Intrusion (FMVSS 214)

One experimental lightweight door was mounted on a car body, then subjected to a quasi-static side pole intrusion test. In this test a short, rigid, 12 inch diameter pole is pushed laterally into the door, which is mounted on a car body that is secured to the floor. (see Figures 14 and 15). Load on the pole is recorded during the 18 inches of intrusion of the pole into the door (Figure 16), and average loads ("crush resistances") are computed during the first 6 inches and first 12 inches of intrusion. For the Mg door tested, the average crush resistances during 6-inch intrusion and 12-inch intrusion were 13.2 kN and 17.0 kN, respectively, and exceeded the 10.0 and 15.6 kN minimums specified in the Standard. The peak was 28.1 kN, very close to the specified minimum of 31.1 kN.

Damage to the lightweight door was observed during this pole intrusion test, as shown in Figure 17. In addition to breakage of the glass, there was tearing of the aluminum outer panel near the bottom edge of the pole, and cracking of the magnesium inner panel at the following locations: (a) latch, (b) fore/aft midpoint of the beltline, (c) forward mounting location for the outer belt reinforcement, (d) forward mounting location for the steel anti-intrusion beam and (e) near the hinges. There was little or no cracking of the lowest portion of the inner panel, near the rocker.

Results of the quasi-static side pole intrusion test show that there is opportunity to improve the door design in order to increase peak crush resistance and to also manage the location and timing of fracture events.

Based on the amount of damage observed and the lower-than-required peak load observed in the quasi-static test, the project team decided not to conduct the dynamic test for this design.

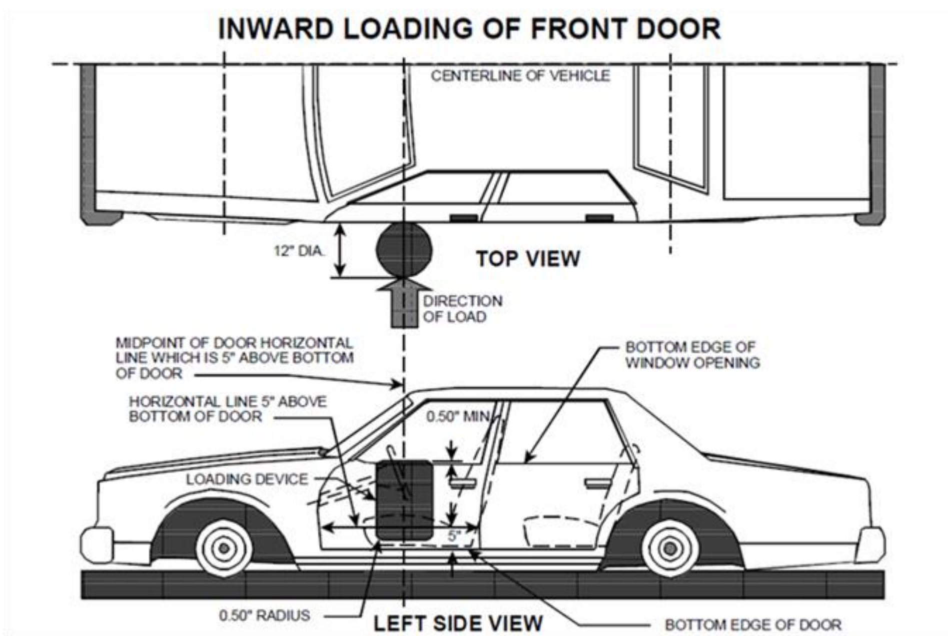


Figure 14. Graphic showing test setup for FMVSS 214 Static test procedure in which a rigid, short, 12" (305 mm)-diameter pole is pressed laterally against a side door.

(a) (b)

Figure 15: (a) Photograph of an experimental Mg door (black) on a Buick LaCrosse car body, before quasi-static side pole intrusion testing, viewed from (a) inside the car and (b) outside the car.

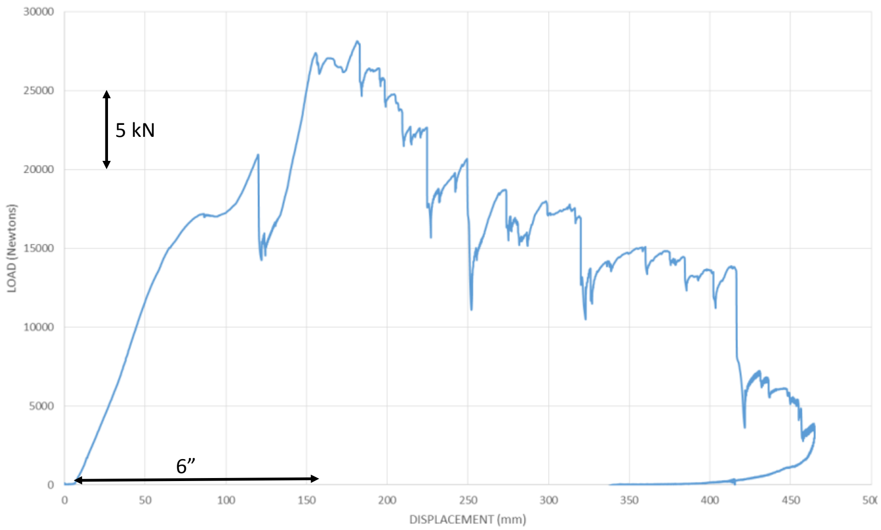


Figure 16: Ram load vs. displacement (intrusion) curve for quasi-static side pole intrusion test of Mg door.

(a) **(b)**

Figure 17: (a) Photograph of an experimental magnesium door after quasi-static side pole intrusion test. (b) Photograph of the aft lower corner of the door shown in (a).

5.5 Life Cycle Analysis

A goal of the project was to "develop an integrated die casting (IDC) process for large, thin-walled structural magnesium alloy panels that will reduce process steps, materials usage, and part count, thereby reducing the embedded energy in the manufacturing value chain. The IDC will improve energy productivity by at least 50% compared with multi-piece, multi-step steel stamping and joining processes". To address this goal, life cycle analysis (LCA) using Argonne National Laboratory's GREET models was used to determine energy consumption and global warming potential during the following sequential phases of life:

1. Material Production. This is essentially the processing of ores into metal ingots.
2. Material Transformation. This is conversion of metal ingots into the form which goes into Part Production. For sheet metal it is typically a combination of hot rolling and cold rolling. For die castings there isn't any Material Transformation because the ingots made in Material Production go straight to Part Production.
3. Part Production. This phase converts the metals into useful components. For the steel and aluminum sheets this is done by stamping. For the magnesium this is done by melting the ingots then rapidly pushing the liquid metal into large metal dies. (Note: the energy associated with actually making finished doors out of component parts isn't addressed here because either (a) they were considered to be nearly equal for the steel and Mg doors (such as hemming the outer panels onto the inner panels) or (b) the magnitudes were estimated to be very small relative to the sums of Material Production, Material Transformation, and Part Production (for example, the energy of spot welding of a steel door is approximately 10 MJ, which is small compared to the 1000 MJ sum of Material Production, Material Transformation, and Part Production.)
4. Use. During this phase the vehicle is assumed to be driven 200,000 miles (321,800 km) in a combination of city and highway conditions.

The analysis was conducted using published data and methods, and typical industry values of various inputs, such as: ratio of recycled metal to primary metal, percent material utilization (inverse of engineered scrap) in part production processes, miles driven on highway vs. miles driven in city, etc. One exception is that the choice of cover gas used during die casting was taken to be the modern CO_2-based, SF_6-free, type rather than the historical SF_6-based type. This greatly reduces the global warming potential (GWP) associated with Part Production because the GWP of SF_6 is 24,000 times that of CO_2. Another exception is that the primary-Mg production process was chosen to be 100% electrolysis (typical of North American production and the new large plants elsewhere) rather than the recent global production mix of 83% Pidgeon process and 17% electrolysis. This results in an energy of Material Production of 252 MJ/kg rather than 325.

The LCA revealed that the embedded energy of manufacture of the Mg door is almost twice that of the steel door (1882 vs 994 MJ), but the cumulative energy demand (CED) is 17% lower for simple door-material substitution, and 38% lower for the combination of door-material substitution and powertrain downsizing (assuming 200,000 miles of driving). (see Figures 18 and 19). In other words, the energy benefit associated with the lightweight door is due to the improved fuel economy of the vehicle in service rather than with the manufacturing processes. The "break-even" points (defined as the number of miles driven at which the CED of the Mg door equals that of the steel door) is 72,000 miles for simple door-material substitution, and 40,000 miles for the combination of door-material substitution and powertrain downsizing.

Of the manufacturing portion of the CED, the energy of actually making the stampings or castings is small compared to the energy of the preceding steps of reducing ores to metals and rolling ingots into sheets. Therefore, the embedded energy of manufacture of the Mg door could in theory be reduced to approximately that of the steel door by using all recycled Mg rather than the industry average 53/47 ratio of recycled to primary. In order to have the embedded energy of the Mg door be 50% of that of the steel door, both the Mg content and the Al content must be made largely of recycled metals. Specifically, the Mg should be 96.5% recycled rather than 53%, and the Al sheet should be 93.5% recycled rather than 11%.

Figures 20 and 21 compare the global warming potential of the different doors, with and without powertrain downsizing. As with CED, the GWP benefit of the Mg door occurs during the in-service use of the vehicle, rather than in manufacturing.

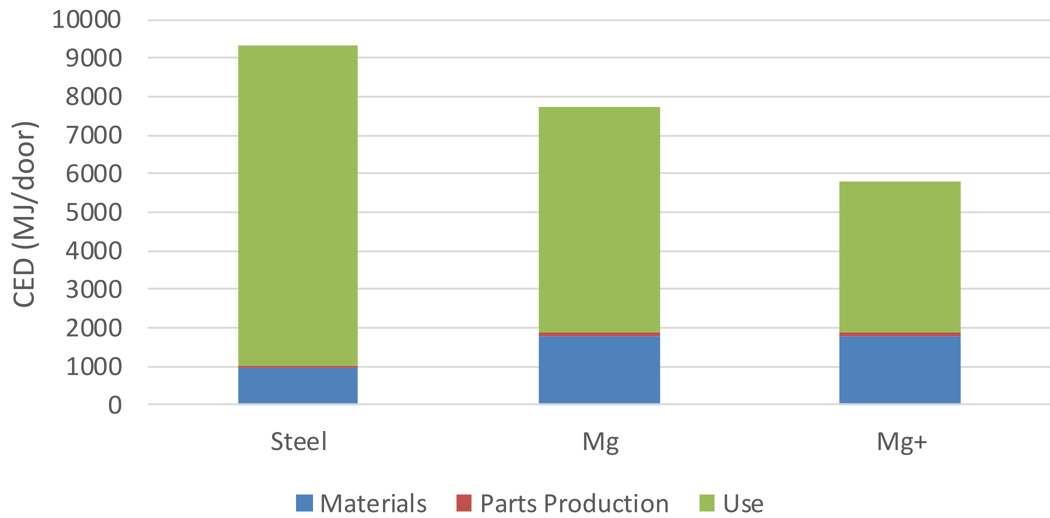


Figure 18: Graphical comparison of energy consumption associated with the 18 kg steel door structure, the 9.7 kg Mg door structure, and the 9.7 kg Mg door structure with downsizing of vehicle powertrain ("Mg+"). The "Use" portion is for 200,000 miles (321,800 km) of driving.

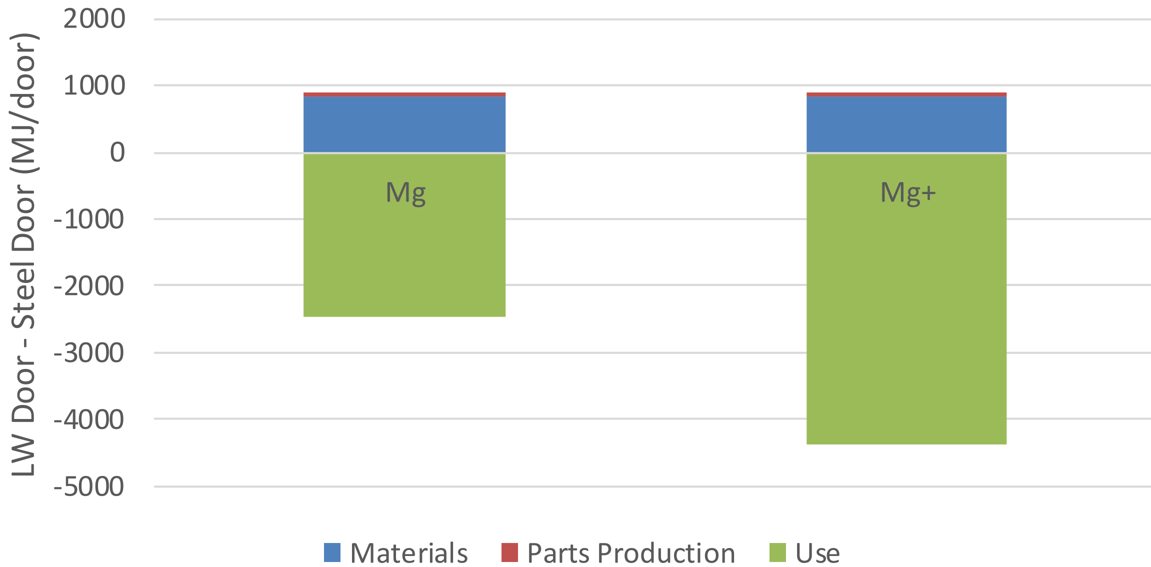


Figure 19: Graphical comparison of energy consumption difference, relative to the steel door, associated with the 9.7 kg Mg door structure, and the 9.7 kg Mg door structure with downsizing of vehicle powertrain. The "Use" portion is for 200,000 miles (321,800 km) of driving.

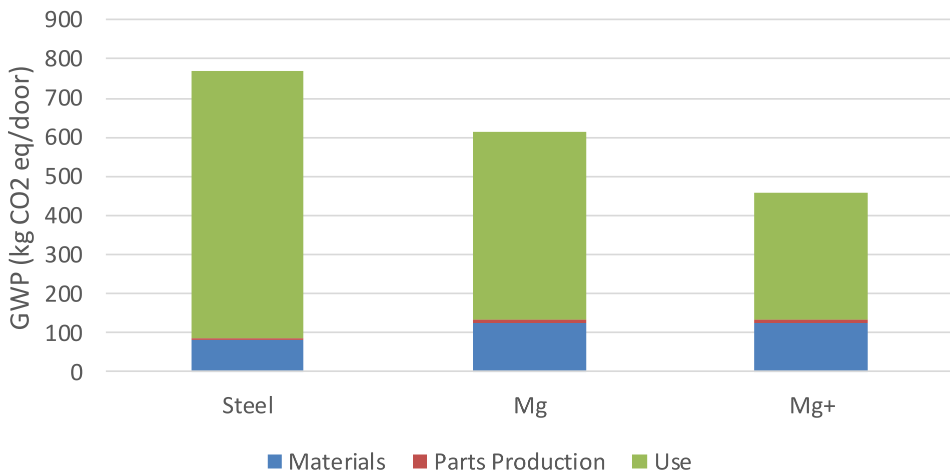


Figure 20: Graphical comparison of global warming potential associated with the 18 kg steel door, the 9.7 kg Mg door, and the 9.7 kg Mg door with downsizing of vehicle powertrain ("Mg+"). The "Use" portion is for 200,000 miles (321,800 km) of driving.

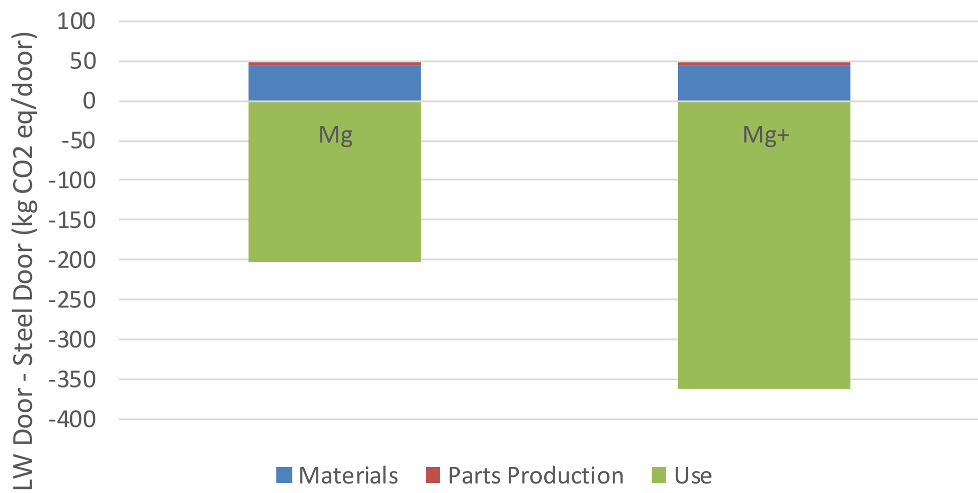
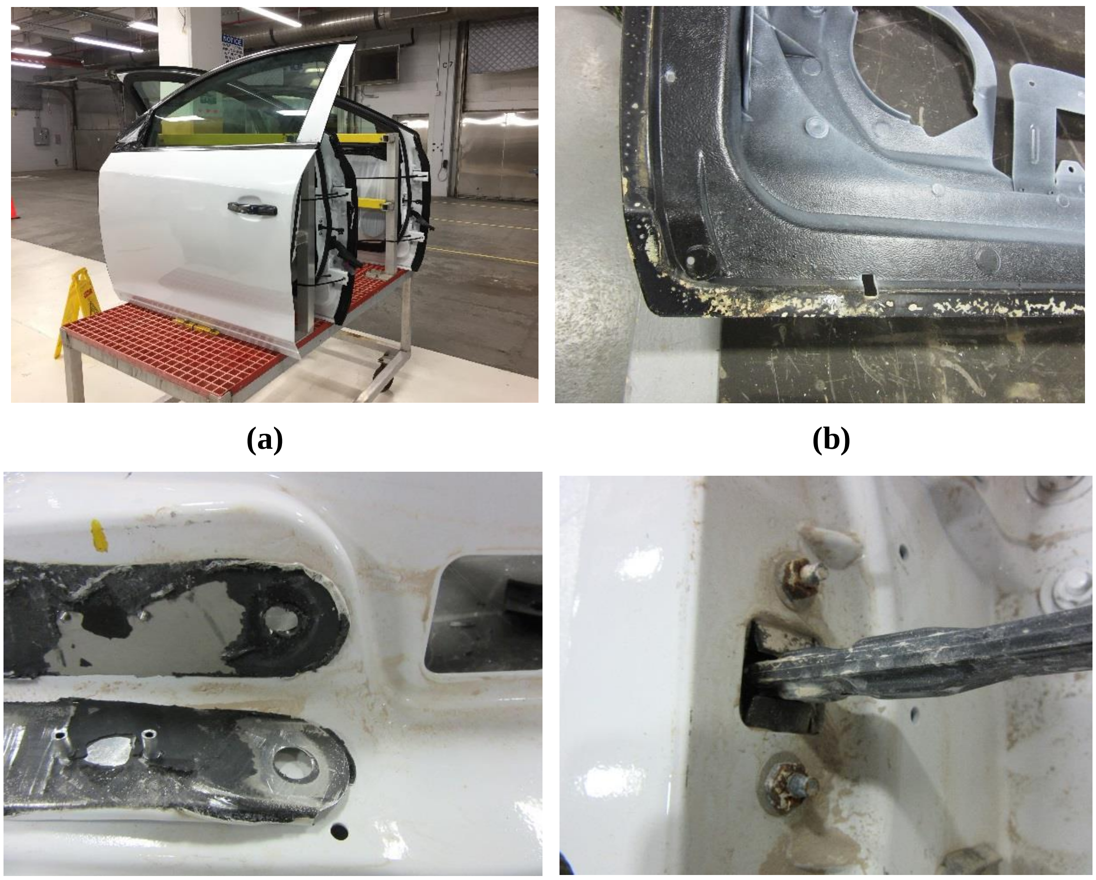


Figure 21: Graphical comparison of global warming potential difference, relative to the steel door, associated with the 9.7 kg Mg door, and the 9.7 kg Mg door with downsizing of vehicle powertrain. The "Use" portion is for 200,000 miles (321,800 km) of driving.

5.6 Corrosion

Accelerated corrosion testing was done on both fully assembled experimental doors incorporating AM60 inner panels and on small coupons of AM60, AZ91, and AT72-based alloys. The former was to check for corrosion due to galvanic couples or crevices which may hold saltwater, and the latter was to compare the inherent general corrosion of different alloys. Testing of doors followed a version of the GMW14872 accelerated cyclic corrosion test procedure, which comprises three 8-hour segments in each 24-hour cycle. The first includes spraying with a salt water solution while at room temperature and humidity. This is followed by 8 hours in a water fog humidity climate of

100% relative humidity at 50 ºC. Then eight hours of air drying in a climate of <30% relative humidity at 60 ºC. This cycle was repeated 44 times in order to provide the "equivalent" of fifteen years of field exposure in a 95%-tile region, such as Montreal. After the test exposures, the doors were visually inspected, disassembled, and then visually inspected again. No corrosion was seen on either the magnesium or aluminum components, but some red rust was seen on the steel nuts that help attach the checklink mechanism to the inner panel. (see Figure 22).



(a) **(b)**

(c) **(d)**

Figure 22: Photographs of corrosion-test doors. (a) Doors mounted on cart prior to exposures. (b) Aft lower corner of inner panel. (c) Hinge mount including adhesive-backed aluminum isolator, and square hole for wiring. (d) Nuts on checklink mounting screws show red rust. Note: (b), (c), and (d) show a door after accelerated cyclic corrosion testing and door disassembly. The light spots along the lower edge of the door panel in (b) are bits of hem adhesive.

The new AT72 alloy was tested for salt spray (ASTM-B117) corrosion resistance, along with baseline alloys AZ91D and AM60B test plates (20 mm x 20 mm squares). All surfaces were covered with a lacquer to prevent corrosion except for one as-cast surface which was exposed to an intense saline fog in the chamber. After 168 hours in the salt spray chamber multiple samples of each alloy were removed and visually examined. The AT72 samples were found to experience less corrosion than AM60B but slightly more than the highly corrosion resistant AZ91D alloy, as shown in Figure 23. These experiments show that the corrosion rate of AT72 alloy is between those of AM60B and AZ91D alloys.

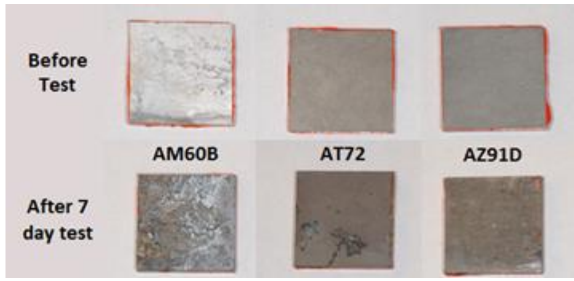


Figure 23: Corrosion test plates before and after 168 hours in the salt spray chamber.

5.7 Overcasting

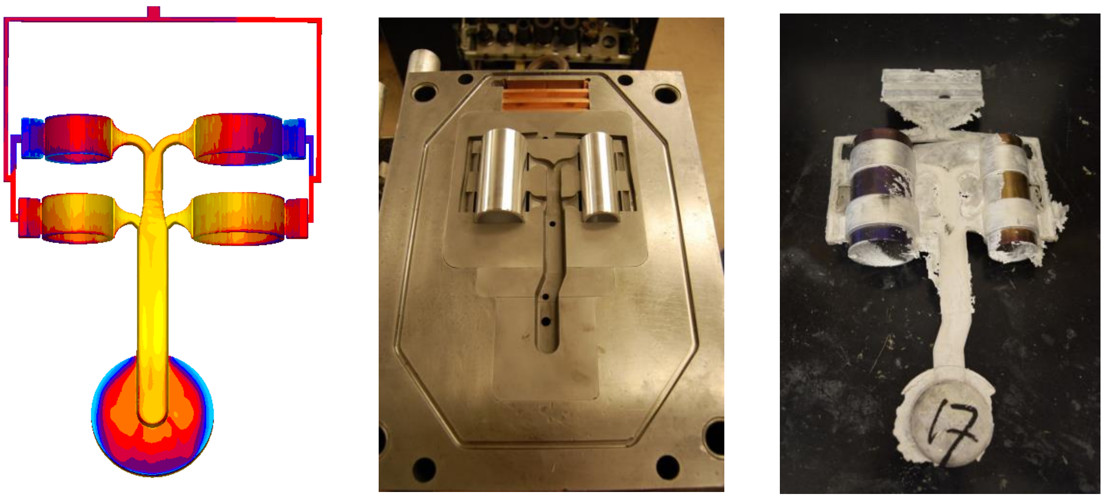
A goal of the project was to explore the concept of casting a magnesium alloy onto a piece of aluminum (or steel) that is accurately held in the die, and would thereby become part of the finished product. Such overcasting has been used commercially in other systems, such as die casting of aluminum alloys onto iron cylinder liners in the production of blocks for internal combustion engines. Initially it was envisioned that this project would overcast in both a small die in the lab and a large door panel die in a plant. The latter was not done, due to (a) anticipated increase in cycle time associated with and operator placing aluminum pieces in the die, (b) difficulty in securing aluminum pieces in the die, and (c) difficulty in preventing molten magnesium leakage around edges of the aluminum pieces.

AM60 magnesium alloy was die cast onto tubes of steel and aluminum in a die that was designed and built specifically for fundamental study of the process. (see Figure 24). The tube diameters were 1.5 and 2.0 inches (38 and 51 mm), and the cast ring wall thicknesses were 1.5 and 3.0 mm, thereby giving four geometry combinations in each casting. After trimming the casting to remove the gating and flash, the tubes were cut radially to yield four samples. These were characterized in terms of interfacial shear strength and interface microstructure.

Interface shear behavior was tested with the apparatus shown in Figure 25a, and resulted in force vs. displacement curves like those in Figure 25b. The force rose rapidly until ring sliding began, then decreased to a plateau as sliding continued. The jagged shape of the curves is attributed to the surface roughness left on the tubes by machining. For both tube diameters, the samples having 3 mm ring wall thickness showed higher peak and plateau forces than those with 1.5 mm walls, but the difference was more pronounced for the larger diameter tubes. (see Table 2). The interfacial shear strengths were on the order of 10 MPa, so there is opportunity to increase strength by either enhancing metallurgical bonding or adding geometrical features, such as pre-cut keyways in the tube, which would lead to mechanical interlocking of tube and ring when the magnesium solidifies.

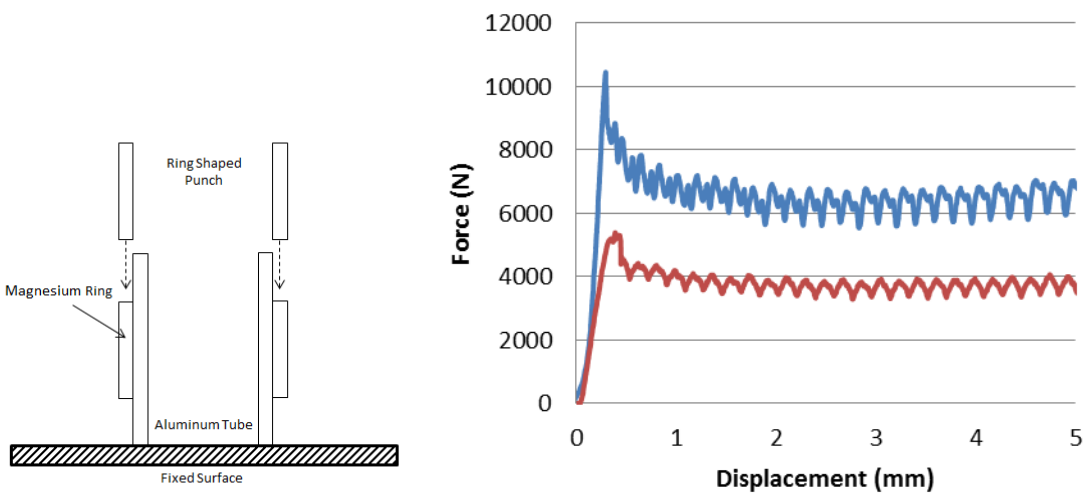
The microstructure of the interface region between the aluminum tubes and the magnesium rings was characterized in terms of gap size and reaction layers visible in transverse sections. (see Figure 26a-d). Generally speaking, there were no interface gaps at most circumferential locations, 80-

100 μm gap near the gate inlet, and 15-30 μm gap near the overflow outlet, i.e., the gaps are associated with regions of greatest thickness and diverging or converging flows. Interfacial reaction layers (Figure 26d) were found on the samples having 3 mm rings, but not on those having 1.5 mm rings, presumably due the greater amount of heat available to initiate the reactions.



(a) **C**

Figure 24: Overcasting of magnesium onto tubes. (a) Graphic showing biscuit, gating, ring castings, and overflows. (b) Photograph of ejector half of die, including aluminum tubes. (c) Photograph of casting that was made onto steel tubes.

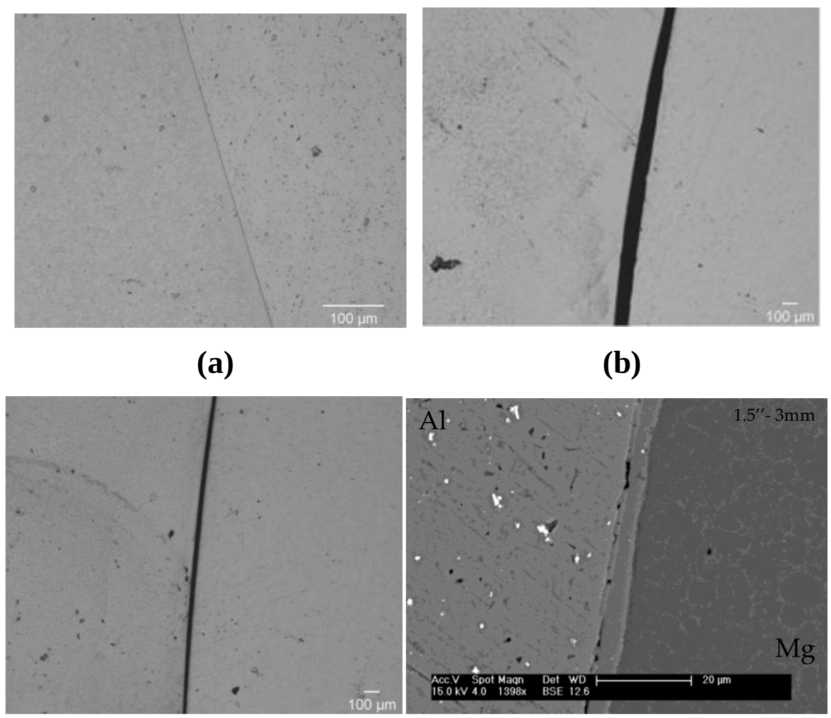


(a) **(b)**

Figure 25: (a) Graphic showing longitudinal cross section of apparatus for testing interfacial axial shear strength of overcast ring/tube samples. (b) Chart of force vs. ring displacement for samples having 2-inch diameter aluminum tubes and 3mm ring (top curve) or 1.5mm ring (bottom curve).

Table 2: Peak loads required to axially shear AM60B overcast rings along aluminum tubes.

Tube Diameter (inch)	Ring Thickness (mm)	Load(N)
1.5	1.5	6181
1.5	3	8273
2	1.5	5886
2	3	10904



(a) **(b)**

(c) **(d)**

Figure 26: Optical micrographs of interface region of magnesium die cast onto aluminum tube at different circumferential locations. Direction of viewing is axial. (a) No interface gap at most locations. (b) 80-100μm gap near gate inlet. (c) 15-30μm gap near overflow outlet. (d) Reaction layers between Al and Mg found in some areas of thick (3mm vs 1.5mm) rings cast onto tubes.

5.8 Alloy Development

The current die cast magnesium alloys are based on the Mg-Al system with AZ91D (Mg-9Al-0.7Zn) and AM50/60 (Mg-5/6Al-0.4Mn) being the most used commercial alloys. This is because of the excellent castability, corrosion resistance, and strength at room temperature resulting from the addition of aluminum. These Mg-Al alloys contain two phases including matrix α-Mg and β-$Mg_{17}Al_{12}$ which precipitates at the grain boundaries and softens at low temperatures (120°C).

These discontinuous precipitates also lead to a reduction in ductility at higher weight fractions. Other elements, such as Sn found in the AT72 (Mg-7Al-2Sn) alloy, are needed to achieve a higher increase in strength without a large reduction in ductility. As an alloying element in Mg, Sn is found to improve the strength and also creep resistance of the alloys. CALPHAD (CALculation of PHAse Diagrams) simulation predicted that no ternary phases would form in a Mg-Al-Sn system, and die casting experiments confirmed this. Instead a binary intermetallic phase Mg_2Sn is precipitated along with the β-$Mg_{17}Al_{12}$ phase. The Mg_2Sn phase is stable at higher temperatures with a melting point at 770°C and provides extra strengthening.

The project studied Mg-7Al-2Sn-based alloys with additions of Si up to 1.5%, then focused on an alloy with 0.75% Si addition. This alloy exhibits higher hardness than the base alloy, and age hardens at 200 ºC with a broad peak at approximately 65 hours. (see Figure 27). It also shows a high yield strength of 190 MPa in this peak-aged T5 condition, but a rather low tensile ductility of 2.4% elongation. (see Table 3). In the as-cast condition, it shows slightly higher strength and slightly higher ductility than AZ91, but significantly higher strength and significantly lower ductility than AM50/AM60 alloys. Relative to as-cast AM60+CaO it has slightly higher strength and significantly lower ductility.

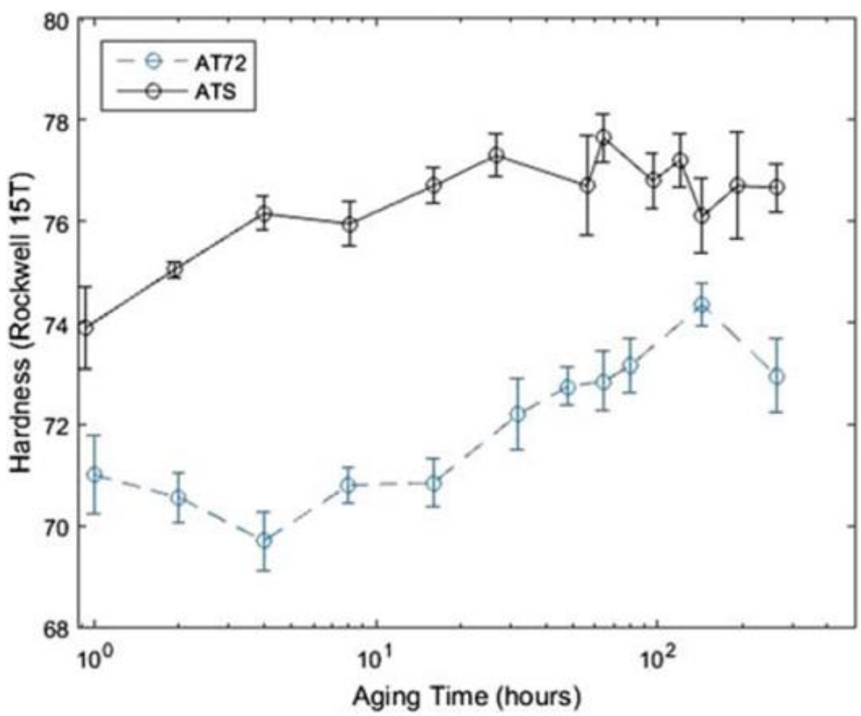


Figure 27: Chart of age hardening of AT72 (Mg-7Al-2Sn) and ATS (Mg-7Al-2Sn-0.75Si) alloys at 200 ºC. (Copyright 2017 by The Minerals, Metals & Materials Society. Used with permission.)

Table 3: Tensile properties, including yield strength (YS) and ultimate tensile strength (UTS) of AT and ATS alloys from this project, and AZ and AM alloys from various sources.

Alloy	Condition	YS, MPa	UTS, MPa	Elong., %
ATS	As-cast	161	222	4.0
ATS	T5 65h@200C	190	221	2.4
AT72	As-cast	149	195	3.5
AT72	T5 65h@200C	160	191	1.7
AZ91D	As-cast	150	230	3
AM60B	As-cast	131	220-240	6-13
AM50A	As-cast	124	220-228	10-15
AM60 + CaO	As-cast	155	-	14

5.9 Super-vacuum Die Casting and Tensile Properties

Super-vacuum die casting (SVDC) is a variant of high-pressure die casting in which the die cavity is evacuated to approximately 50 mbars just prior to molten metal being pushed in at very high speed by the plunger. It is used routinely with aluminum alloys to make high-integrity structural parts with very low levels of entrapped-gas porosity, which improves mechanical properties and allows for solution heat treatment without blistering, or fusion welding. The IDC project sought to exploit SVDC to enhance the mechanical properties of magnesium structural castings, and thereby help make them more competitive with steel stampings.

Tensile properties of magnesium alloy bars cast with and without vacuum are shown in Figure 28 and Table 4, and generally show a positive effect of vacuum. The greatest effect was observed with the AT72 alloy in which elongation increased from 2.0 to 3.7%, presumably due to reduced gas porosity, thereby allowing for more strain hardening to occur and increase the UTS from 172 to 197 MPa. It should be noted that the cavity vacuums achieved were typically 100-150 mbar, rather than the 50 mbar super-vacuum. Had the project consistently achieved 50 mbar vacuum during casting of these bars, higher average values and reduced standard deviations of UTS and % elongation might have been achieved.

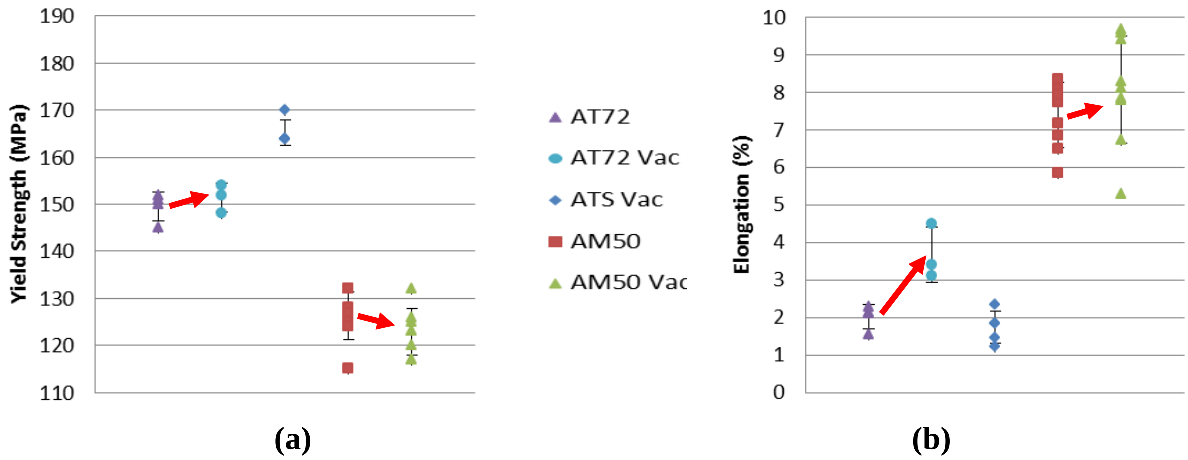


Figure 28: Charts of tensile properties of magnesium alloys cast with and without vacuum. (a) Yield strength. (b) % elongation. The red arrows indicate the effects of vacuum casting on AT72 and AM50 alloys.

Table 4: Average tensile properties of magnesium alloy bars cast with and without vacuum. Standard deviations are shown in parentheses.

Sample	Non Vacuum /Vacumm	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
AT72	No Vac	149.5 (3.1)	172.2 (7.2)	2.0 (0.3)
AT72	Vac	151.3 (3.0)	**196.7 (5.3)**	3.7 (0.7)
ATS	Vac	**165.2 (2.7)**	180.8 (8.6)	1.7 (0.4)
AM50	No Vac	125.6 (5.1)	186.2 (16.7)	7.0 (1.5)
AM50	Vac	122.2 (5.0)	190.9 (18.4)	**7.6 (2.1)**

Super-vacuum die casting of door inner panels in AM60 alloy was done during the last casting trial. It led to filling problems in which some regions of the die didn't receive molten metal before freezing occurred. This issue was attributed to excess cooling and partial solidification of molten metal in the shot sleeve during the time that it took to establish vacuum in the die cavity. Changes in die casting process parameters were made which reduced but didn't consistently eliminate the filling problem. A next step which could be taken would be electrical heating of the shot sleeve to reduce heat loss from the molten metal to the shot sleeve.

In summary, although in theory the application of super-vacuum to die casting of magnesium should result in less entrapped gas porosity and associated benefits, this project saw very practical challenges in realizing the process (i.e., < 50 mbar cavity vacuum) and fully achieving the expected benefits. Additional work on vacuum systems and thermal systems would be needed to meet these goals.

SECTION 6: SUMMARY OF ACCOMPLISHMENTS AND MILESTONES

Accomplishments

The following accomplishments were achieved.

1. Design and manufacture of a large thin-wall structural magnesium die casting having minimum wall thickness of 2 mm.
2. Approximately 50% mass reduction with the lightweight magnesium/aluminum door-in-white structure compared to the steel baseline. (However, the experimental doors didn't meet some of requirements of side doors during mechanical testing.)
3. Life cycle analysis of cumulative energy demand of lightweight and baseline doors-in-white.
4. Developed Mg-Al-Sn-Si alloys, and their heat treatments, which have higher strength and lower ductility when compared to AM60 alloy.
5. Overcasting of magnesium rings of different wall thicknesses onto steel tubes and aluminum tubes of different diameters. The resulting "subassemblies" were free of gross defects.

Milestones

The Milestone Log is shown in Table 5.

Table 5: Project Milestone Log

No.	Milestone	Planned completion	Actual completion
1	Test specimen die delivered.	3Q2013	3Q2013
2	Test specimen die modified for vacuum and flat plate	1Q2015	1Q2015
3	Melting furnace, gas mixer, controls, pump installed	3Q2014	3Q2014
4	Overcasting die designed and simulation completed	2Q2014	3Q2014
5a	AT alloys corrosion tested (round 1) and compared with AZ91 and AM60	2Q2014	2Q2014
5b	Corrosion testing (round 2)	3Q2015	3Q2015
6	Die cast Mg door inner panel with header designed	2Q2014	3Q2014
7	Die for casting Mg inner panel designed	3Q2014	3Q2014
8	Test specimens cast in AT and AM alloys with super vacuum, and process parameters delivered	4Q2016	3Q2016
9	Overcasting die built	1Q2015	1Q2015
10	Overcasting trials run and process parameters delivered	2Q2016	3Q2016
11	Chemical composition of an improved ATS (Mg-Al-Sn-Si) alloy finalized	4Q2015	4Q2015
12	Test specimens cast in ATS (Mg-Al-Sn-Si) alloys with super vacuum	4Q2016	4Q2016
13	Die for casting Mg inner panel built	2Q2015	2Q2015
14	First Mg inner panels cast and process parameters delivered	2Q2015	2Q2015
15	Al outer panel, outer beltline reinf, and pull handle strap stamped	3Q2015	3Q2015
16	First doors assembled	1Q2017	1Q2017
17	Delivery of specimen, component and door system test results	3Q2017	3Q2017
18	Delivery of energy efficiency of integrated die casting process	3Q2017	4Q2017

SECTION 7: CONCLUSIONS AND RECOMMENDATIONS

1. Large thin-wall magnesium alloy (AM60) high-pressure die castings for potential use in full-headered side doors on cars may be designed and successfully cast.
2. The mass of the magnesium/aluminum door structure is approximately 50% of that of the baseline steel door structure.
3. The embedded energy of manufacture of the lightweight door structure is twice that of the steel version. This added energy of manufacture would be offset by the improved fuel economy of the vehicle during driving. The break-even point would be at 70,000 miles, or at 42,000 miles if the powertrain was downsized. The results of life cycle analysis for global warming potential (greenhouse gas emissions) is similar to that for energy. The break-even mileages could theoretically be reduced by (1) further lightweighting of the magnesium/aluminum door or (2) greatly increasing the ratio of recycled metal to primary metal in that door.
4. The lightweight door passed accelerated corrosion tests, but cracked during durability testing and during side pole intrusion testing. Modification of the casting design would be required to reduce or eliminate such cracking.
5. Additional work would be needed to demonstrate significant benefit of super-vacuum HPDC of the magnesium alloys and parts studied. Electrical heating of the shot sleeve is recommended in order to reduce partial solidification of metal in the shot sleeve while waiting for vacuum to be established in the die cavity.
6. Mg alloys containing 7%Al, 2%Sn, and up to 1%Si exhibit age hardening at 200 ^{o}C. They are stronger than the AZ91D alloy and have comparable ductility. Optimization of the die casting process parameters likely would help to increase the ductility of these alloys. The corrosion behavior of these alloys is between those of the AM60 and AZ91 alloys.
7. Overcasting of magnesium onto either steel or aluminum pieces is physically possible and potentially beneficial for some structures. For any proposed overcast design, work likely would be required to achieve adequate interface strength and to determine if overcasting is an economical solution.
8. Commercialization planning of the type of lightweight door technology addressed in this project would be contingent upon the door meeting all technical performance requirements of the car maker. The specific lightweight door developed in this project didn't meet some of those requirements, but a preliminary business case study was conducted anyhow. This study considered the ratio of cost increase to mass decrease when the lightweight door is compared to a baseline steel door. The ratio was found to be in an acceptable range for some vehicle programs, especially if the number of such vehicles to be produced is equal to or slightly less than the estimated 250,000-shot life of the die set. This would allow for the investment in the dies to be spread across many parts and thereby help reduce the cost increase.

SECTION 8: PRODUCTS DEVELOPED UNDER PROJECT AND TECHNOLOGY TRANSER ACTIVITIES

A. Publications

The following publications and presentations have been delivered since project inception:

- Berkmortel, R. (2014): “Magnesium - Are Technological Developments Allowing It To Be More Competitive?“, Presentation at American Metal Market Conference 13th Aluminum Summit • May 15-16, 2014, Philadelphia.
- Berkmortel, R.; Wang, G.; Jekl, J.; and Petrillo, J. (2015) “Magnesium Applications in the Automotive Industry and the Developing Trends”, 10th China Diecasting Congress & Exhibition, Shanghai, July 8-10, 2015.
- Carter, J. (2014): “Development of Integrated Die Casting Process for Large Thin-Wall Magnesium Applications“, Presentation given at DOE AMO Peer Review, Washington DC.
- Carter, J. (2015): “Development of Integrated Die Casting Process for Large Thin-Wall Magnesium Applications“, Presentation given at DOE AMO Peer Review, Washington DC.
- Carter, J. (2015): “Development of Integrated Die Casting Process for Large Thin-Wall Magnesium Applications“, Presentation given to USCAR’s Materials Technology Team, Southfield, MI.
- Carter, J. (2016): “Development of Integrated Die Casting Process for Large Thin-Wall Magnesium Applications“, Presentation given at DOE AMO Peer Review, Rosslyn, VA.
- Carter, J. (2017): “Development of Integrated Die Casting Process for Large Thin-Wall Magnesium Applications“, Presentation given at DOE AMO Peer Review, Arlington, VA.
- Jekl, J.; Auld, J.; Sweet, C.; Carter, J.T.; Resch, S.; Klarner, A.D.; Brevick, J.; and Luo, A.A. (2015); “Development of a Thin-Wall Magnesium Side Door Inner Panel for Automobiles”, International Magnesium Association’s 72nd Annual World Magnesium Conference, May 17-19, 2015, Vancouver.
- Klarner, A.; Sun, W.; Meier, J.; Luo, A. (2016); “Development of Mg-Al-Sn-Si Alloy Using a CALPHAD Approach”, Presented at TMS 2016, Nashville, TN, February 2016, and published in conference proceedings Magnesium Technology 2016, Eds., A. Singh, K. Solanki, M.V. Manuel, M. Alderman and N.R. Neelameggham, TMS, Warrendale, PA, 79-82.
- Klarner, A.D.; Sun, W.; Miao, J.; Luo, A.A. (2017); “Microstructure and Mechanical Properties of High Pressure Die Cast Mg–Al–Sn–Si Alloys”. In: Solanki K., Orlov D., Singh A., Neelameggham N. (eds.) Magnesium Technology 2017. The Minerals, Metals & Materials Series. Springer, Cham

- Klarner, A.D. (2017) "Development of Mg-Al-Sn and Mg-Al-Sn-Si Alloys and Optimization of Super Vacuum Die Casting Process for Lightweight Applications", December 2017. Doctoral dissertation, The Ohio State University.
- Sun, W.; Zhang, C.; Klarner, A.D.; Cao, W.; Luo, A.A. (2015) "Simulation of Concurrent Precipitation of Two Strengthening Phases in Magnesium Alloys", Presented at TMS 2015, Orlando, FL, March 2015, and published in conference proceedings Magnesium Technology 2015, Eds., M.V. Manuel, A. Singh, M. Alderman and N.R. Neelameggham, TMS, Warrendale, PA, 289-293.

B. Websites or other Internet Sites

- No websites featuring project work or results were developed or updated since project inception websites or other internet sites developed for this project.

C. Networks or Collaborations Fostered

- Oher than the project team, no networks or collaborations were developed since project inception.

D. Technologies / Techniques

The following technologies and techniques have been developed since project inception:

- Mg-Al-Sn and Mg-Al-Sn-Si alloys were developed, as were age-hardening heat treatments for these alloys.

E. Inventions/Patent Applications/Licensing Technologies

- One invention disclosed resulting in patent application below.
- General Motors patent application filed and published (#US20160096418A1 dated 04-07-2016) entitled "Stiffeners for Cast Light-metal Door Headers" with inventors Jon T. Carter and Anil K. Sachdev.
- No licensed technologies were submitted since project inception.

F. Other Products

- No other products were produced since project inception.

G. Awards, Prizes, and Recognition

- "Award of Excellence – Automotive Cast Product", International Magnesium Association, Singapore, May 2017.

"Excellence in Magnesium Die Casting" award. North American Die Casting Association Die Casting Congress & Tabletop, September 18-20, 2017.