# Development of a Thin-Wall Magnesium Side Door Inner Panel for Automobiles

**J. Jekl, J. Auld, C. Sweet**
Meridian Lightweight Technologies, Strathroy, Ontario, Canada

**J.T. Carter, S. Resch**
General Motors, Warren, Michigan, USA

**A.D. Klarner, J. Brevick, A.A. Luo**
The Ohio State University, Columbus, Ohio, USA

## Abstract

Cast magnesium side door inner panels can provide a good combination of weight, functional, manufacturing and economical requirements. However, several challenges exist including casting technology for thin-wall part design, multi-material incompatibility and relatively low strength vs steel. A project has been initiated, supported by the US Department of Energy, to design and develop a lightweight frame-under-glass door having a thin-wall, full die-cast, magnesium inner panel. This development project is the first of its kind within North America. Phase I of the project is now complete and the 2.0mm magnesium design, through casting process enablers, has met or exceeded all stiffness requirements, with significant mass reduction and part consolidation. In addition, a corrosion mitigation strategy has been established using industry-accepted galvanic isolation methods and coating technologies.

## Introduction

The project is developing an integrated die casting (IDC) process for large, thin-wall 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 process will improve energy productivity by at least 50% compared with multi-piece, multi-step steel stamping and joining processes typically used to make car door inner panels. The lightweight car door inner panel product will reduce vehicle mass, and thereby improve handling and fuel economy during the life of the vehicle.

The IDC innovation is addressing 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 (1.5-2mm) in magnesium casting applications for mass efficiency (current state of the art for large thin-wall magnesium castings is 2.5-3.0mm). This will be accomplished using advanced tooling design including casting simulation and capability of super vacuum die casting to enable heat treatment of AT72 (Mg-7%Al-2%Sn[1]), a new high-strength magnesium alloy. 2) Consolidate the multi-piece door structure into one large single-piece casting with part integration beyond what is possible with conventional die casting. 3) Use overcasting for regions needing reinforcement or isolation. 4) Use advanced process simulation tools for process optimization.

Die castings have been used before in various side door structures [1], but this is the first project published in the open literature involving the entire inner panel (lower portion and the “header” portion around the window opening) cast in one piece. Such a design helps increase stiffness, reduce part count, and avoid joining operations.

## Project Scope

This project addresses design of product, tooling and process as well as testing of a thin-wall die cast magnesium door inner panel. It is divided into the three phases discussed below.

<u>Phase 1: Die design, simulation & manufacturing</u>
Three dies are being used to address the subjects of super vacuum, high-strength alloy, overcasting, and large thin-wall die casting. One produces ASTM standard specimens for

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[1] All compositions in wt.% except otherwise stated.

mechanical and corrosion testing. A second overcasts magnesium "collars" onto aluminum or steel tubes which are placed in the die prior to closing. The third will produce an experimental structural inner panel for a side door on a recent GM production car. All three have super vacuum capability, and were designed using simulation tools to model die fill and solidification.

In addition to the dies, a front, left-hand, side door for a recent GM sedan was designed to utilize a magnesium die casting in place of several steel stampings. This design also uses some newly designed aluminum stampings in place of steel ones, as well as some carry-over parts from the original door design. The requirements of a door structure and challenges in designing a lightweight door will be discussed below.

Phase 2: Casting process development

The development of process parameters for casting magnesium alloys is underway for all three dies. The two smaller dies will run on a 250-ton die casting machine, and the door panel die will run on a 3200-ton machine. Based on the simulation results from Phase 1, key experiments are being run to generate/validate the optimum process parameters (such as vacuum level, slow shot velocity, fast shot velocity, die temperature, die spray and blow off pattern, total spray time, die lube ratios, metal temperature, shot pressure, and dwell time) for casting of AM60 and AT72 magnesium alloys.

Phase 3: Testing and validation

The various castings generated during Phase 2 are used for both mechanical (monotonic and cyclic) and corrosion testing. Also, experimental doors will be hand-assembled using the die cast inner panels and typical prototyping processes. The assemblies will be subjected to static-, cyclic-, impact-load testing, and corrosion testing, to determine their performance relative to the required performance specifications. A final assessment of the embedded energy in the manufacturing chain will be conducted in order to verify the 50% reduction which was determined in the preliminary assessment.

## Magnesium Door Design Challenges

The door structure (Figure 1) of an automobile is an integral part of the vehicle structural system. Typically, the side door structure performs the following functions: The door provides structure to resist intrusion from other vehicles or objects, absorbs energy and transfers loads in an appropriate manner to other areas of the vehicle and keeps occupants safely inside the vehicle. It provides attaching surfaces for mechanisms, wiring, sensing devices, seals and interior trim. In addition, the door keeps the vehicle closed to the outside environment.

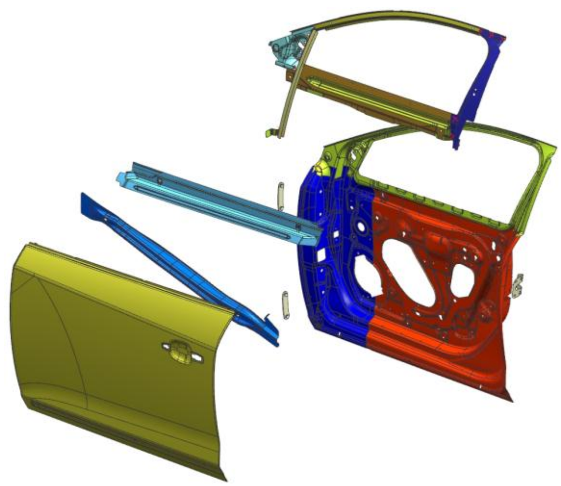

Figure 1. Graphic showing the components in a conventional door assembly.

The mechanisms attached to the door structure includes mirror, inside and outside handles, hinge and hold open device, latch and window regulator systems. In all of these examples, the attaching surfaces must be sufficiently rigid so that the hardware will operate satisfactorily. Examples of insufficient stiffness conditions include mirror shake due to wind, road, engine or speaker inputs, deflection of attaching surface during handle or window regulator operation, door frame shake/shudder, panel vibration, etc. These conditions reduce customer satisfaction and are to be avoided.

The door structure provides surface and attachments for door mounted seals as well as surfaces and features that interface with body mounted seals. The glass system seals and decorative moldings are also located, supported and retained by the door structure. All seals keep wind, water, dust and noise out of the passenger compartment.

The interior trim attached to the door structure is supported and retained by the structure. Support surfaces for pull handles, arm rests, garnish moldings, sunshades, speakers, etc.

must be rigid enough to avoid noticeable deflections, creaks, groans, rattles and buzzes. The structure also provides a sealing surface for the water deflector which maintains a dry environment for the occupants.

Structurally, the door contributes to occupant protection and resists loads from aerodynamic wind, door slam and hold open forces, as well as general use/abuse loads. Typical load/test cases include vertical rigidity, torsion, beltline, mirror attachment and upper frame stiffness of the door structure while constrained by the latch and door hinges. These load cases are evaluated for elastic deflection and permanent set.

Design of a die cast magnesium panel to effectively replace a welded assembly of steel stampings leads to challenges in both the process and the materials. For example, whereas steel stampings may be welded together to create stiff closed sections (like box beams), die castings generally must be cast with open sections to allow for part ejection. Typically there is no additional room in door structures to allow for the use of bigger sections, and therefore stiffening of the open section is accomplished by the addition of deep ribs. This is critical when replacing steel with magnesium because the inherent material stiffness (elastic modulus) of the latter is about one-fifth that of the former. (Fortunately, the density is about one-fifth also.)

Vehicle mass reduction (aka "lightweighting") is an important goal to help auto makers improve the fuel economy of engine-powered vehicles and extend the range of electric vehicles. Additional benefits of lightweighting include improved acceleration, braking, and handling, and reduced wear rates of certain components. Lightweighting of side doors is also important because it influences the opening and closing efforts required of the driver and passengers. Traditionally side door structures have been made from stamped steel panels and reinforcements, joined together with spot welds, hems, and hem adhesives. This approach utilizes the high formability and weldability of sheet steel to make highly functional and attractive doors. Now the industry is working to reduce door mass but maintain the functionality and beauty. Various materials (higher strength steels, magnesium, aluminum, and reinforced polymers) and manufacturing methods (stamping, casting, and molding) are being explored by various automotive OEMs and their suppliers.

## Casting Design

For panels like side door inners, the die casting approach has the advantages over stampings of being able to increase wall thickness locally and add stiffening ribs where needed to handle stresses. These allowed for our design to eliminate the need for several reinforcements (inner beltline, mirror patch, latch, header, B-pillar, etc.) which are used in conventional door design, but still to meet the performance requirements. See Figure 2.

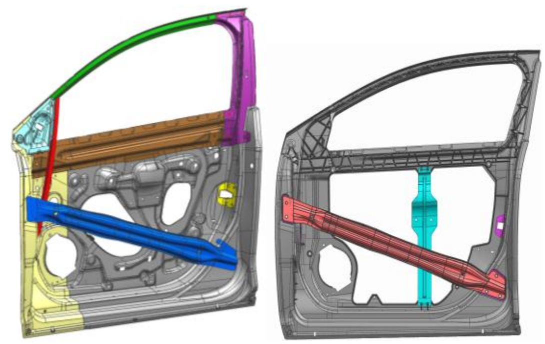

Figure 2. Graphics showing the components in a conventional door inner assembly (left) and in a die-cast magnesium (gray) door inner assembly (right). Not shown are the stamped outer panels and the stamped outer beltline reinforcements, which would be similar for both assemblies.

Finite element analyses were used throughout the design process to ensure that the door would meet the mechanical loading requirements, and also be lightweight. One of the challenging requirements is called "header stiffness". In this test a 150 N load is applied to the header in the outboard direction as shown in Figure 3. The resulting elastic deflection must be less than a specified amount, which varies with vehicle type, model year, and region. Header stiffness is calculated as the ratio of N of load to mm of deflection. Achieving a header stiffness with the open-section magnesium design comparable to the closed-section steel design was challenging due to both the open section and the reduced elastic modulus. However, careful design work resulted in a header stiffness of 51 for the new design, which is very close to the value of 52 for the baseline steel door.

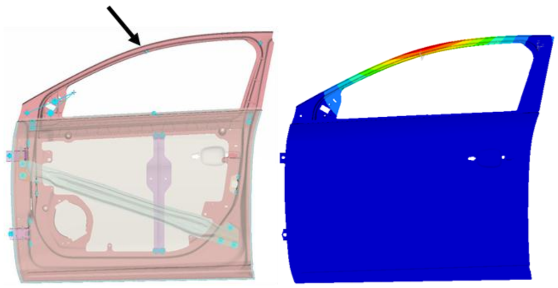

Figure 3. Graphics showing the magnesium door structure design with an applied test load (left) and the FEA output showing the resulting deflections (right).

The mass of the new door structure design is about half that of the baseline steel door. i.e., 9.2 kg vs. 18.0 kg. Part of the reduction is due to careful design work and the low density of magnesium, and part (2.6 kg) is due to the use of aluminum stampings rather than steel stampings for the outer panel and the outer beltline reinforcement. (The use of aluminum in place of steel for the outer panel also greatly reduces the probability of galvanic corrosion of the magnesium inner panel in the hem joint, which holds the outer and inner panels together.)

### Design for Corrosion

Corrosion protection of magnesium in side doors is a challenge because water or saltwater can get inside the door cavity by flowing down the glass, and because the magnesium structure generally must contact “more-noble” dissimilar metals resulting in galvanic corrosion couples. To reduce the chance of corrosion of a magnesium inner panel in a door (or liftgate or decklid), it is necessary to properly coat the inner panel prior to attaching anything to it. Such coating of a panel, rather than coating of the complete door structure assembly, adds a step to the typical car door/body manufacturing process. One coating combination which is used successfully on magnesium car parts consists of a thin conversion coating plus 40-150 microns of epoxy powdercoat. In applications where a steel part contacts a magnesium part, such as a steel bolt head against a magnesium housing cover, it is common practice to place 5000/6000 series aluminum sheet metal isolation between the two [2]. For the case of the steel bolt head, an aluminum washer with a diameter at least 10 mm greater than that of the bolt head could be placed between the head and the housing cover. That would result in at least 5 mm of exposed aluminum outside the bolt head which would have to be bridged by droplets of water in order for the steel and magnesium to form a galvanic corrosion couple. Both the organic coating combination and aluminum isolators will also be used on the experimental magnesium door. See Figure 4. Less extensive isolation might be used in different areas of the vehicle where exposure to moisture is less.

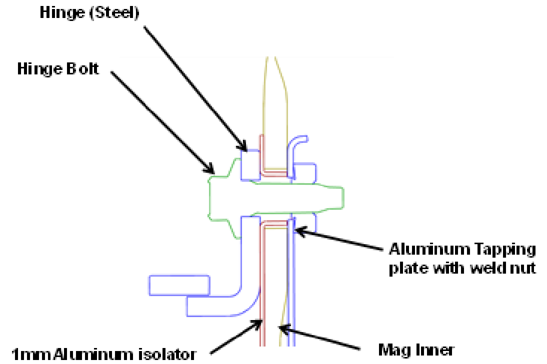


Figure 4. Graphic showing a typical bolted joint design concept with an aluminum isolator between steel and magnesium components to reduce the chance of galvanic corrosion.

### Design for Manufacturing

<u>Tool layout</u>
For this application, the overall size and shape of the casting was going to be the same as the steel sheet metal, therefore, it was decided to take the steel CAD model to complete some initial feasibility and die layout studies. This involved overlaying the door inner model onto the 3200T die casting machine (DCM) platen to assess critical aspects such as; basic clearances to tie bars, shot positions, projected area, and gating.

Several die layout concepts were considered, however, none of these concepts provided acceptable parameters for manufacturing this particular casting. Therefore, we opted to gate the casting within the inner panel region, which offered several benefits to the overall layout.

<u>Casting geometry</u>
As mentioned above, header stiffness was one of the critical performance requirements of the door inner. Figure 5 shows the optimization of the cross sectional geometry that was required to maximize stiffness while at the same time,

minimize mass and promote good filling and solidification characteristics. Mg-A design had reasonable stiffness, but the parting line was not desirable. Mg-B design had higher stiffness; however, this geometry would result in high amounts of gas and shrinkage porosity. Mg-C design offered a basic section which took advantage of the entire packaging space while at the same time, maintained constant wall thickness, simple parting line and good flow characteristics. The final optimized shape and rib pattern is shown as Mg-Final.

Due to the size of the door inner, multiple inserts are required within each half of the tool. The seam line between these inserts is a location where an upstanding flash line will be evident on the casting surface. In the visible and hemming areas, this flash line would have to be ground and polished smooth. To minimize the cost associated with this secondary operation, special design features were incorporated into the tool at these locations as shown in Figure 6 below.

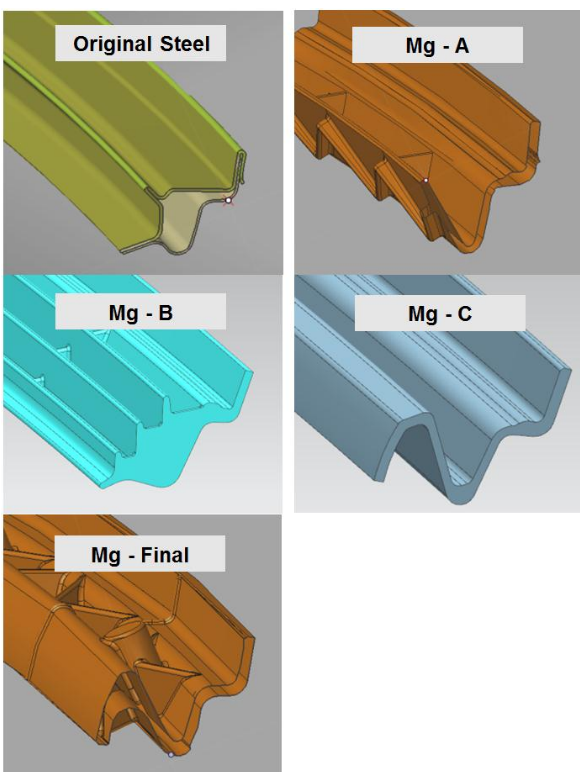

Figure 5: Header frame design evolution.

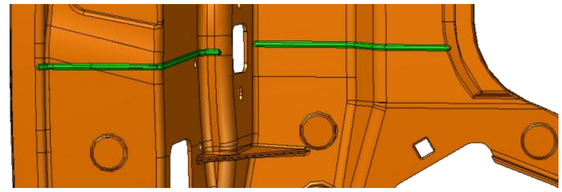
Figure 6: Example of insert split line design feature.

### Simulation and Tooling Development

During the development of the gating system, we needed to understand the performance requirements of the door inner as well as define the ‘critical’ structural regions. Figure 7 shows these areas, namely; hinge locations, beltline, latch and crash intrusion beam mounts. Using this information, process and gating calculations were performed based on minimal wall stock of 2.0mm.

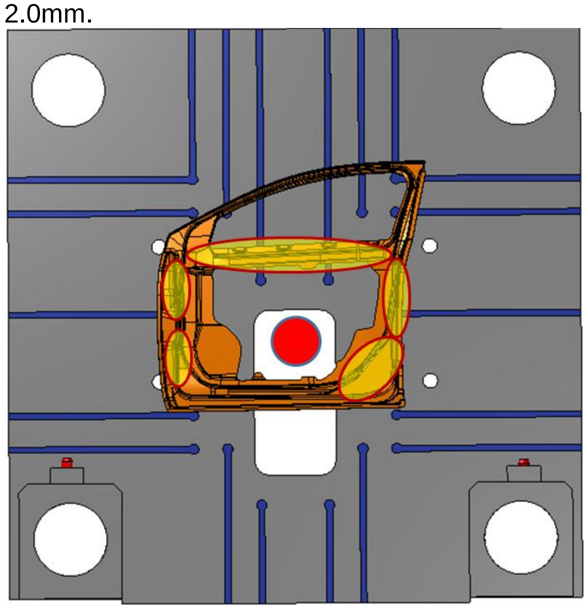
Figure 7: Final die layout with inner panel removed to allow for optimal gating.

An initial solidification simulation was analyzed once the design concepts were finalized. This is shown in Figure 8 which indicates solidification characteristics of the casting. Areas that are visible indicate the last to solidify regions of the casting.

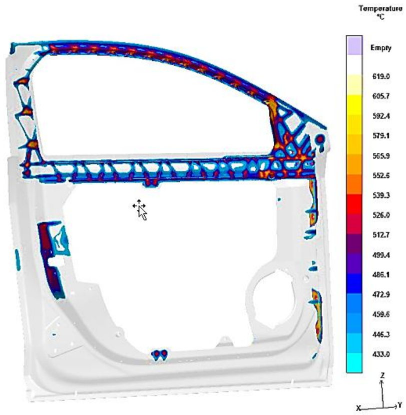

Figure 8: Solidification temperature.

Initial filling simulation results are shown in Figure 9. The LH image shows areas where high levels of air entrapment occur within the casting during filling. In addition, the RH image shows the metal temperature distribution around the casting at the end of the filling process. Using these results in combination of other key simulation output, several simulation iterations were completed until the runner, gating, overflow and venting/vacuum design was optimized to ensure good metal flow characteristics throughout the castings, especially in the critical locations.

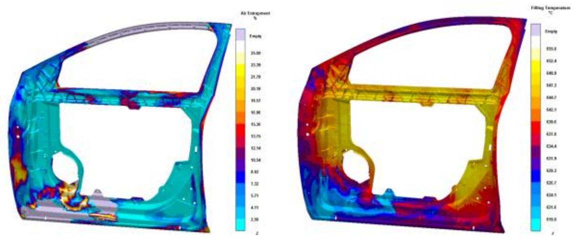
Figure 9: Results from 1$^{st}$ gating design. Air entrapment during filling (LH), Metal temperature at end of filling (RH).

Another critical aspect of the tool design is the internal heating and cooling strategy. Simulation was used to establish several different zones where thermal control is required. These zones are controlled using thermocouples embedded in the die at strategic locations and integrated into the casting cell PLC for continuous monitoring and control. These zones are designed to help optimize the filling process as well as managing the heat load during solidification.

The die was also designed with SVDC (super vacuum die casting) capabilities. As with all vacuum die casting methods, die sealing is critical in achieving maximum vacuum levels in the cavity, therefore, sealing of potential leakage paths has been accounted for. Measurements of the vacuum levels inside the tool will be taken at two different locations to help understand the effect of vacuum level on the casting process.

Figure 10 is the completed cover die design model for the Mg door inner.

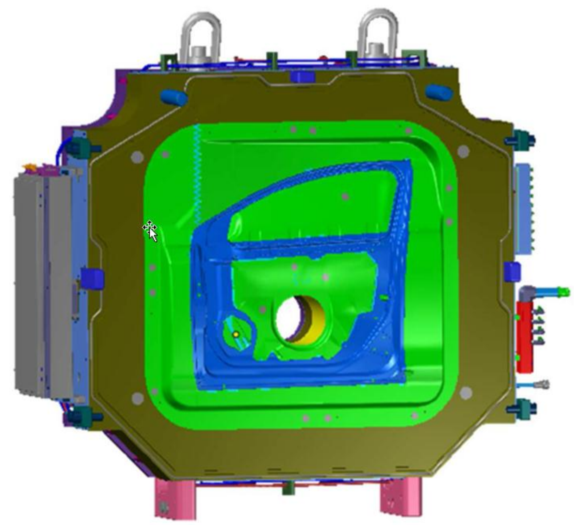

Figure 10: Cover die model.

**Alloy design and 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) [3]. 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 [4]. CALPHAD (CALculation of PHAse Diagrams) simulation [4] predicted that no ternary phases would form in a Mg-Al-Sn system and die casting experiments confirmed this [5]. 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 [5].

The new AT72 alloy was tested for salt spray (ASTM-B117) corrosion resistance, along with baseline alloys AZ91D and AM60B test plates (2cm x 2cm 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, Figure 11. These initial experiments show the corrosion rate of AT72 alloy is between those of AM60B and AZ91D alloys.

In addition to a baseline alloy (AM60), the new high-strength AT72 alloy will also be used in the die casting trials of thin-wall magnesium door inner casting this project.

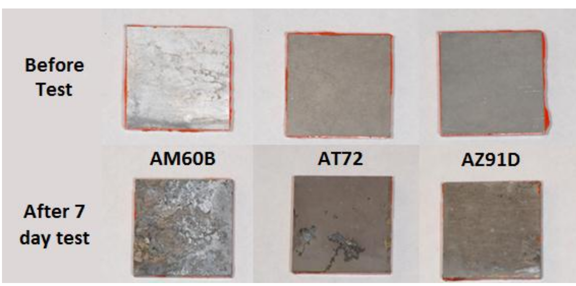


Figure 11: Corrosion test plates before and after 168 hours in the salt spray chamber.

## Super Vacuum Die Casting

High pressure die casting (HPDC) is a very efficient way to produce magnesium parts. However, because of the turbulent flow of the molten metal entering the die, air is entrapped producing porosity in the cast parts. Porosity is detrimental to structural properties of castings and also makes them unacceptable for some heat treatments, because the gas porosity expands and causes blistering during the solution treatment. Super vacuum die casting (SVDC) can be used to remove the atmosphere inside the die cavity resulting in less gas porosity in the magnesium parts [5]. To study the differences in mechanical properties between HPDC and SVDC magnesium parts, a 250lb capacity resistance furnace was installed at OSU's 250 ton Buhler die casting machine to accommodate magnesium melting and casting. A HPDC casting run of AM50 alloy has been completed, producing test specimen castings, as a baseline. Modifications on the test specimen die were made to accommodate SVDC, with a vacuum chill plate located at the top of the die and a groove in the die holder to allow for a gasket to be placed around the insert dies. A vacuum system was connected to the die via the chill block. Future SVDC with AM50 and AT72 magnesium alloys will be performed to produce fatigue and tensile bars for comparison of mechanical properties between HPDC and SVDC.

Tensile bars from both processes will be solution treated with the optimized treatment to examine the reduction of blistering by using SVDC. Finally additional aging will be performed to determine the increase in strength of the SVDC process compared with the HPDC process for AT72 die cast parts.

## Heat Treatment Development

The binary Mg-Sn system has a high solubility of 14.85% Sn at 561°C which decreases rapidly to 0.45% at 200°C causing $Mg_2Sn$ phase precipitation, making it a likely alloy for age-hardening. The AT72 ternary alloy is put through a solution heat treatment to dissolve the as-cast $Mg_2Sn$ and $Mg_{17}Al_{12}$ phases into the matrix. The samples were then aged to produce an age-hardening effect. Aging experiments were performed at 200°C, and Figure 12 shows a micro-hardness curve obtained from the experiments. It is evident that there is a ~20% increase of peak hardness after ~75 hours at 200°C. Figure 13 shows a transmission electron microscopy (TEM) bright field image for AT72 alloy aged 30 hours at 200°C, which clearly shows the precipitation of mostly $Mg_2Sn$ phase and some $Mg_{17}Al_{12}$ phase particles. It is obvious that precipitation of both phases is responsible for the age-hardening behaviour in this new alloy system. Work is ongoing to optimize the heat treatment procedures to enhance the mechanical properties of AT72 alloy.

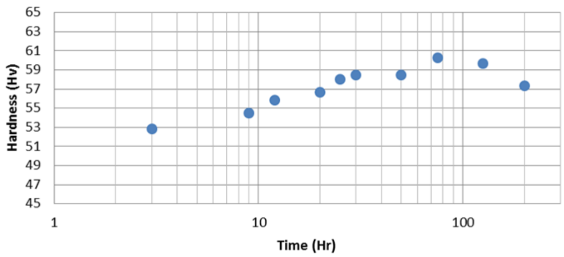

Figure 12: Age-hardening curve for AT72 alloy at 200°C.

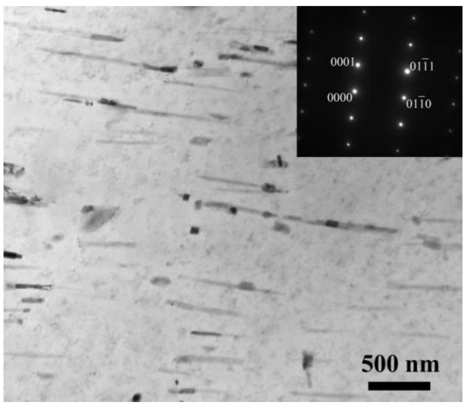


Figure 13: TEM bright field image showing precipitates in AT72 alloy aged 30 hours at 200°C. The beam direction is close to <2-1-10>, and the insert is a diffraction pattern along <2-1-10>.

## Conclusions

A full-headered automotive side door structure has been designed to achieve both mass reduction and part consolidation relative to a typical stamped steel design. The main structural pieces are a die-cast magnesium inner panel, a stamped aluminum outer panel, and a stamped steel impact beam.

Advanced simulation tools were used to design the die cast tooling with special attention being paid to die filling, heat management, and casting solidification. Die construction is underway to provide panels for doors required for testing.

Cast magnesium alloys containing additions of Al and Sn exhibit significant age hardening. Such strengthening might enable down-gaging of select magnesium castings, thereby resulting in additional mass reduction.

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## Acknowledgement

The authors acknowledge the management support from General Motors, Meridian Lightweight Technologies, and The Ohio State University. This material is based upon work supported by the United States Department of Energy under Award Number DEEE005753.