Chapter

Applications of High-Pressure Die-Casting (HPDC) Magnesium Alloys in Industry

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Abstract

High-pressure die-cast (HPDC) magnesium alloys have seen diverse applications in the automotive industry, primarily driven by requirements in internal combustion engine (ICE) vehicles. As the automotive industry is transitioning to an electric vehicle (EV) architecture, there is a great potential for novel applications to improve driving range efficiency. In addition, there is a trend toward larger-sized automotive die castings and an increased interest in aerospace applications due to weight reduction. In this chapter, we reviewed the traditional automotive structural applications in ICE vehicles, as well as current and potential future EV and aerospace applications of HPDC magnesium alloys. The structural applications using AM50, AM60, AZ91 and AE44 magnesium alloys in traditional vehicles can be applied to modern EVs. Additionally, magnesium alloys with varying degrees of higher thermal conductivity, improved castability, superior high temperature properties and flammability need to be developed to replace battery and aerospace in-cabin-related structural materials to meet all safety requirements. Several newly developed magnesium alloys with superior castability are also reviewed for potential automotive and aerospace applications.

Keywords: high pressure die cast (HPDC), magnesium alloy, castability, automotive, aerospace, lightweighting

1. Introduction

There has been an increasing need to reduce the weight of vehicles as forced by emissions and fuel economy legislation. Therefore, lightweighting has become a very important topic for improving power efficiencies while maintaining safety and performance. Several lightweighting strategies, such as product optimization, material substitution and part consolidation, are driven by replacing higher density structural materials with less dense materials.

Magnesium and its alloys have several advantages compared with other automotive metals. Magnesium has a density of 1.74 g/cm^3, which is significantly lower than both aluminum and steel [1]. Magnesium alloys are well known to have excellent specific strength, superior automatability and castability characteristics as well as suitable for the use of self-threading fasteners [2]. Besides the commonly used magnesium alloys which might be unsuitable for service above 150°C [3, 4], heat and creep resistant [5–7] as well as corrosion resistant [8, 9], magnesium alloys have been developed with the addition of appropriate alloying elements. The automotive industry is experiencing a transition in powertrain architectures from internal combustion engine (ICE) to electric vehicles (EV). The development in increasing thermal conductivity of magnesium alloys has supported battery-related applications [7]. On the other hand, flammability resistance has been a hot topic for magnesium alloys, and the related research has gained substantial progress which is highly valuable for aerospace applications [10–19]. Attributed to the above advantages, magnesium alloys have become one of the lightest and most popular structural metals utilized extensively in the automotive industry.

Most magnesium alloy components in industry are manufactured through high-pressure die casting (HPDC) process [20–21] which is illustrated in **Figure 1**. HPDC process offers attractive flexibility in design and manufacturing, excellent die filling characteristics and high efficiency in reduction of secondary processes required by steel structures. **Figure 2** provides a comparison of the yield strength of AZ91 fabricated by several different processes [22–25]. The high strength for that produced by HPDC process is a result of the remarkably fine microstructure from fast-cooling rate. With modern HPDC technologies, magnesium alloys can be produced in near-net shape products with large, thin-wall and complex geometry, exhibiting outstanding structural and functional performance, and therefore has been widely applied as an efficient and cost-saving method especially for high-volume productions.

In the current chapter, the applications of HPDC magnesium alloys in both historical and potential automotive and aerospace industries will be reviewed to provide an overall understanding of the successful examples and ongoing development status.

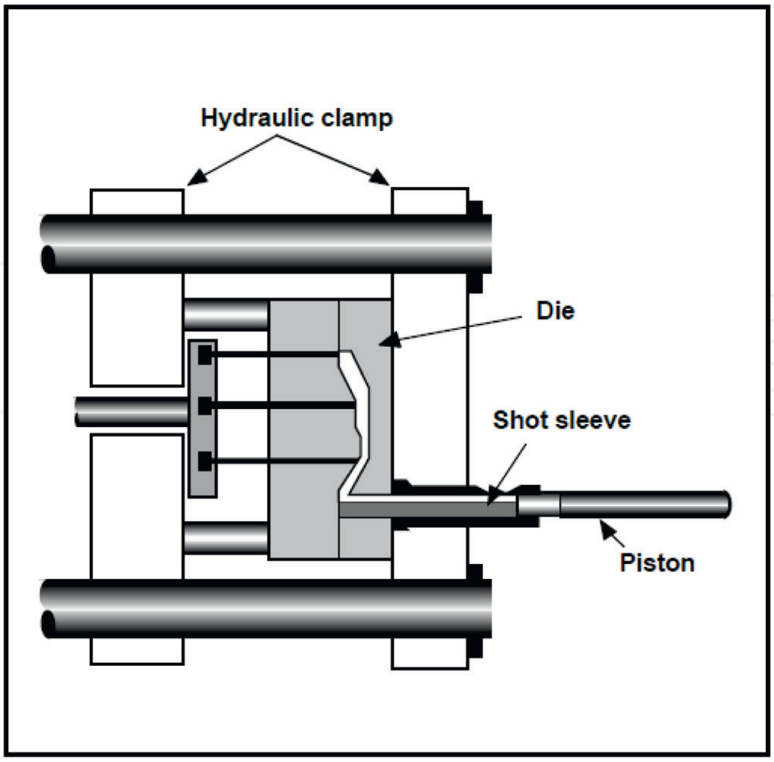

Figure 1.
Schematic diagram showing high pressure die casting (HPDC) process.

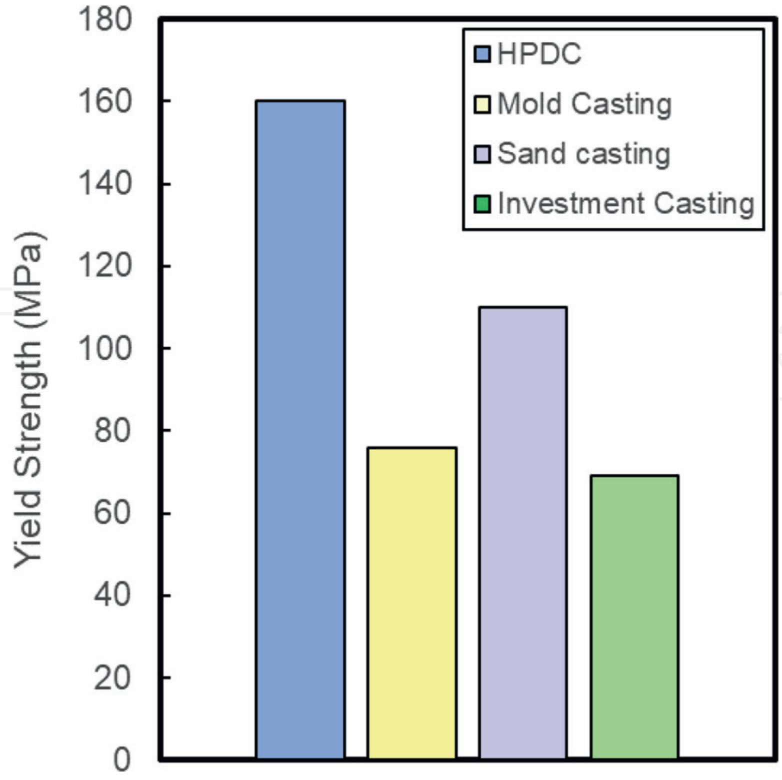

Figure 2.
Comparison of the yield strength of AZ91 fabricated by four different processes [22, 25].

2. Applications of HPDC magnesium alloys

2.1 Traditional applications

Increasing attention has been paid to replace steel and aluminum structural components with magnesium alloys on traditional internal combustion engine (ICE) vehicles in the past several decades. HPDC magnesium alloys have seen a number of these applications. Cost-economic AM50, AM60, AZ91 and AE44 magnesium alloys with excellent castability are most used to manufacture automotive components through the HPDC process. The criteria for component material selection are based on the alloy properties and component service environment.

Figure 3 shows the mechanical [25–27] and corrosion properties of conventional HPDC magnesium alloys and HPDC aluminum alloy A380. The magnesium alloys have comparable yield strength with A380 and similar or better elongations. The mass gains of the as-cast alloys were measured by Meridian Lightweight Technologies at several intervals during salt spray testing (SST) as per ASTM B117 for 1000 hours, to evaluate corrosion properties. It was noted that magnesium alloys AM60B, AZ91D and AE44 showed better corrosion resistance than HPDC A380 aluminum alloy. Based on these properties, the AE44 alloy with high strength and ductility at high temperature is typically used in elevated temperature environments, the AZ91D alloy is selected for high strength, good corrosion resistance and moderate temperature applications, and AM50A/AM60B alloys are utilized where high ductility is required in normal atmospheres.

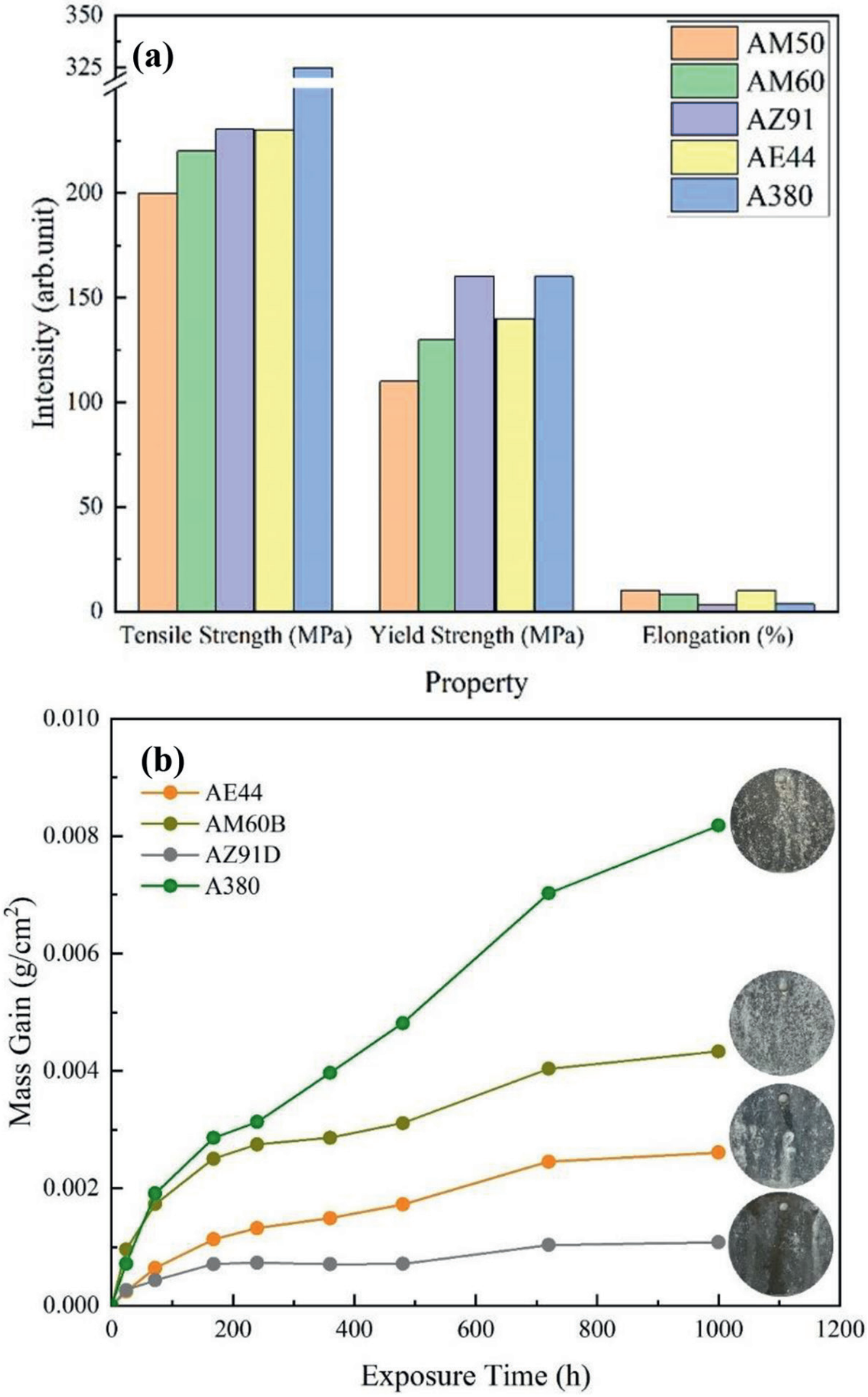

Figure 3.
Mechanical and corrosion properties of conventional HPDC magnesium alloys: (a) mechanical properties [25–27] and (b) salt spray test for 1000 hours conducted by Meridian lightweight technologies.

2.1.1 Interior applications

Magnesium alloy die castings have been widely utilized in interior automotive applications where minimum general corrosion resistance is required. Instrument panel (IP) or cross-car beam (CCB) is one of the earliest interior applications of magnesium alloys in the automotive industry which has been remarkably advanced owing to mass saving requirements in the past two decades. The first and largest die-cast magnesium IP (~12.5 kg) with a wall thickness of ~4 mm was developed by General Motor in 1961 to replace a previous steel IP, which achieved ~25% weight saving [21]. With the optimization of materials and designs, the wall thickness of HPDC magnesium component has been dramatically reduced which has further improved the mass saving efficiency. State-of-the-art one-piece thin-walled cross-car beams can be cast in weights as low as 3 ~ 5 kg.

Figure 4 shows the evolution of the HPDC AM60B magnesium CCB on Jaguar Land Rover (JLR) S-type vehicle from 1998 to present [28]. The initial CCB in **Figure 4(a)** was made of steel which was replaced by the first-generation AM60B magnesium alloy in 2002 ~ 2007 model with a part weight of approximately 5.2 kg. The second-generation was then developed for the model year 2008 XF vehicle with a weight of approximately 5.7 kg and additional contents. With the optimization of design and casting wall thickness, the weight of the third-generation magnesium CCB was reduced to approximately 3.6 kg without decreasing the safety requirement. Although magnesium CCBs have been commonly used in North America and Europe, its application in China market is limited. Hybrid CCB assemblies composed of a half magnesium alloy beam on the driver side and half steel beam on the passenger side were developed on 2017 SAIC Motor Roewe i6, 2019 SAIC Motor Roewe ei5, 2018 NIO ES8 and 2020 BYD Han. These half magnesium CCBs usually have a total width of less than 1 m and weigh 2 ~ 4 kg. There is a significant opportunity to grow the magnesium alloy for one-piece CCB application in China to help meet the mass saving requirements as described in the 2020 Energy-saving and New Energy Vehicle Technology Roadmap 2.0 [29].

Seat frame is another important application of magnesium alloys in the interior automotive. The first concept of using magnesium seatback frame and cushion was demonstrated by Mercedes-Benz AG by using AM50 and AM20 alloys with a total weight ~ 8.5 kg about three decades ago [30]. Several studies and developments were reported on expanding the application of magnesium alloys for seat frames [31–35]. The state-of-the-art magnesium seatback and cushion are found with thinner wall thickness and less weight than before and are more widely utilized on vehicles. **Figure 5(a)** shows the 2014 Chevrolet Corvette Stingray AM60B magnesium backseat with a weight of 1.5 kg which demonstrates greater specific strength than the steel frame it replaced. The side bolsters provide a more supportive and

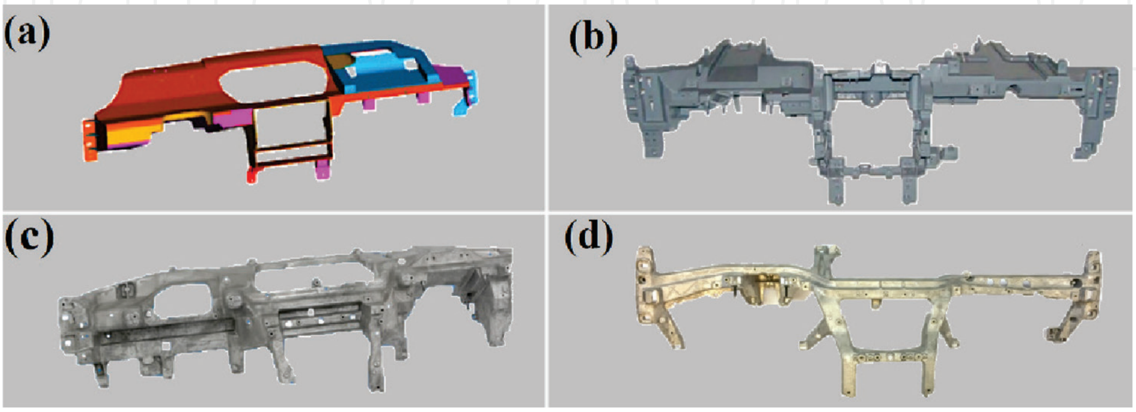

Figure 4.
Evolution of jaguar land rover (JLR) cross car beams (CCB): (a) jaguar S-type 1963 initial design (1998); (b) first-generation magnesium CCB (2002 ~ 2007 jaguar S-type X202); (c) second-generation magnesium CCB (2008–2015 jaguar XF X250) and (d) third-generation magnesium CCB (2015-present XF X260) [28].

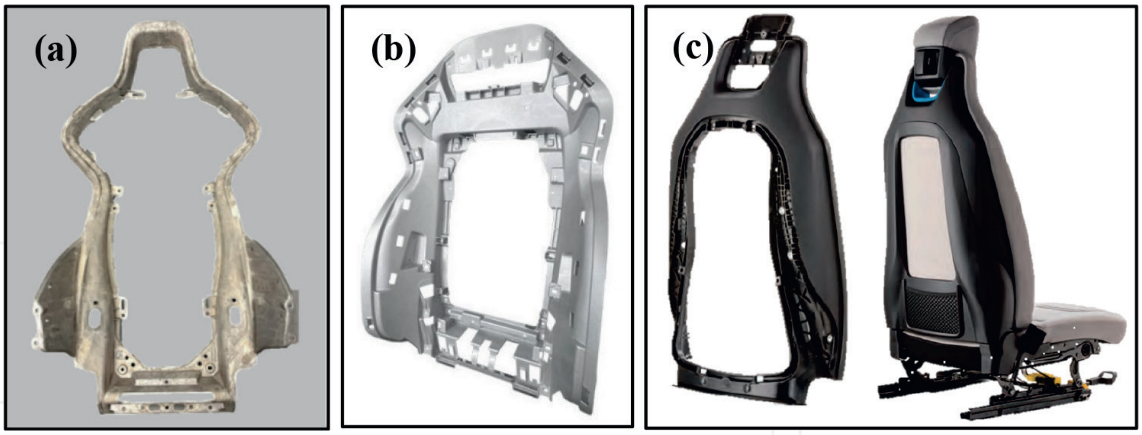

Figure 5.
Images showing backseat applications: (a) 2014 Chevrolet corvette seatback (courtesy of GM); (b) 2015 Mercedes-Benz SLK seatback [37] (courtesy of GF casting solutions) and (c) 2014 BMW i3 seatback [38] (courtesy of BASF).

comfortable seat frame on the competition sport model [36]. **Figure 5(b)** shows the 2015 Mercedes-Benz SLK AM50 magnesium seat which demonstrates a 30% weight saving and received the 2015 "Automotive Cast Design Product" Award of Excellence at the International Magnesium Association (IMA) 72nd Annual World Magnesium Conference [37]. Manufacturing a seatback frame with one-piece HPDC magnesium alloy can have advantages over injection molding using fiber reinforced composite which is another alternative solution for lightweighting. **Figure 5(c)** shows the 2014 BMW i3 back seat made through injection molding using PA66 with long glass fiber by BASF [38]. The plastic seat frame has a weight of 2.3 kg which does show weight reduction over the steel frame it replaced but requires another 2 kg steel reinforcement recliner to maintain strength [38].

Automotive steering wheels made by magnesium alloys AM40B and AM60B have been used since 1987 by Honda Motor [39]. Toyota Motor Corp. also reported the development of a one-piece HPDC AM60B magnesium steering wheel in 1991 [40, 41] which saved approximately 45% weight than the previous steel one. More recently, magnesium steering wheels made of both AM50 [42] and AM60 [43] are widely used in Europe and Asia.

Figure 6 depicts additional automotive interior applications of HPDC magnesium alloys. **Figure 6(a)** shows a HPDC AZ91D Bose audio amplifier made by Twin City Die Casting for automotive application which was awarded the 2014 North America Die Casting Association (NADCA) International Die-Casting Award for Magnesium Over 0.5lbs [44]. The audio amplifier weighs about 0.5 kg and provides both efficient weight saving and good heat dissipation. **Figure 6(b)** and **(c)** illustrates the HPDC AM60 display bracket and steering column manufactured by Meridian Lightweight Technologies. **Figure 6(d)** and **(e)** demonstrates the AM50 front and back center console on Audi A8 [37] and AM60 center stack on JLR Defender manufactured by GF Casting Solutions [45].

Another recent interior application of HPDC AM50A magnesium alloy is the rear support bracket (RSB) manufactured by Meridian Lightweight Technologies in the 2022 Mercedes-AMG SL Roadster as shown in **Figure 7**. This application was awarded the 2022 Automotive Cast Product IMA Award of Excellence at the 79th Annual World Magnesium Conference [46]. Each bracket weighs about 1.9 kg and provides Mercedes-AMG with the most economic weight saving. The bracket was

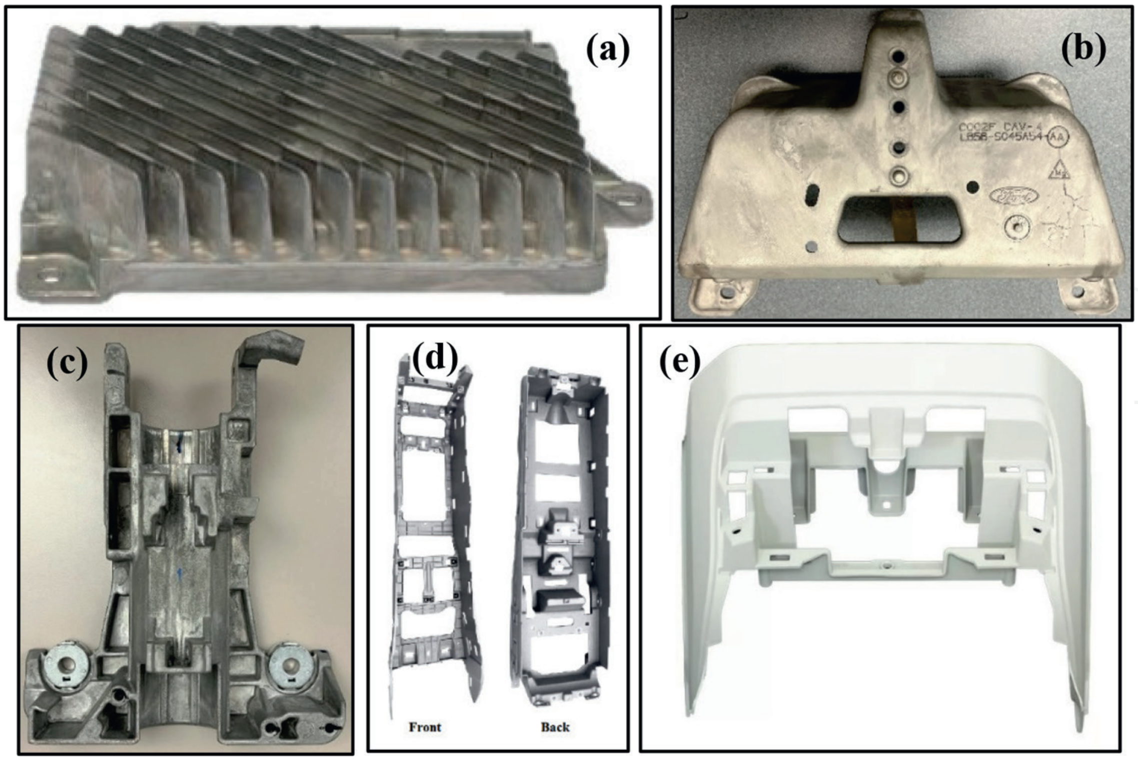

Figure 6.
Images showing interior applications of HPDC magnesium alloys: (a) AZ91D automotive audio amplifier cast by Twin City die casting company [44]; (b) AM60 display bracket on 2021 ford explorer; (c) AM60 steering column cast by Meridian lightweight technologies; (d) AM50 center console on Audi A8 and (e) AM60 center stack on JLR defender [45] (courtesy of GF casting solutions).

Figure 7.
AM50 left hand (LH) and right hand (RH) rear support brackets on 2022 Mercedes-AMG SL roadster cast by Meridian lightweight technologies [46].

able to improve vehicle strength and stiffness, provide spaces for airbags and seatbelt anchorages, contribute to the entire vehicle rigidity improvement and support the second-row backseats. It successfully helped Mercedes-AMG to re-introduce the "2 + 2" seating concept as a standard model. Overall, more efforts are being made to replace interior automotive components with magnesium alloys which demonstrate efficient weight reductions and part consolidation.

2.1.2 Body applications

The concept of utilizing magnesium alloys for automotive body applications was developed about three decades ago and has been significantly scaled up in the recent years. Die-casting roof frames have been used on the Chevrolet C5 Corvette starting in 1997 and again on the Cadillac XLR two passenger roadster since 2003 [21]. The HPDC magnesium radiator support (MRS) was launched by Meridian Lightweight Technologies and Ford Motor Company for the 2004 Ford F-150 truck which was the first ever magnesium front-end application [47]. **Figure 8(a)** shows the overview of the first-generation MRS in 2004. The MRS was made from AM50A magnesium alloy which was assembled with EG60 steel bridging brackets. To minimize the galvanic corrosion between steel and magnesium, several corrosion prevention strategies were

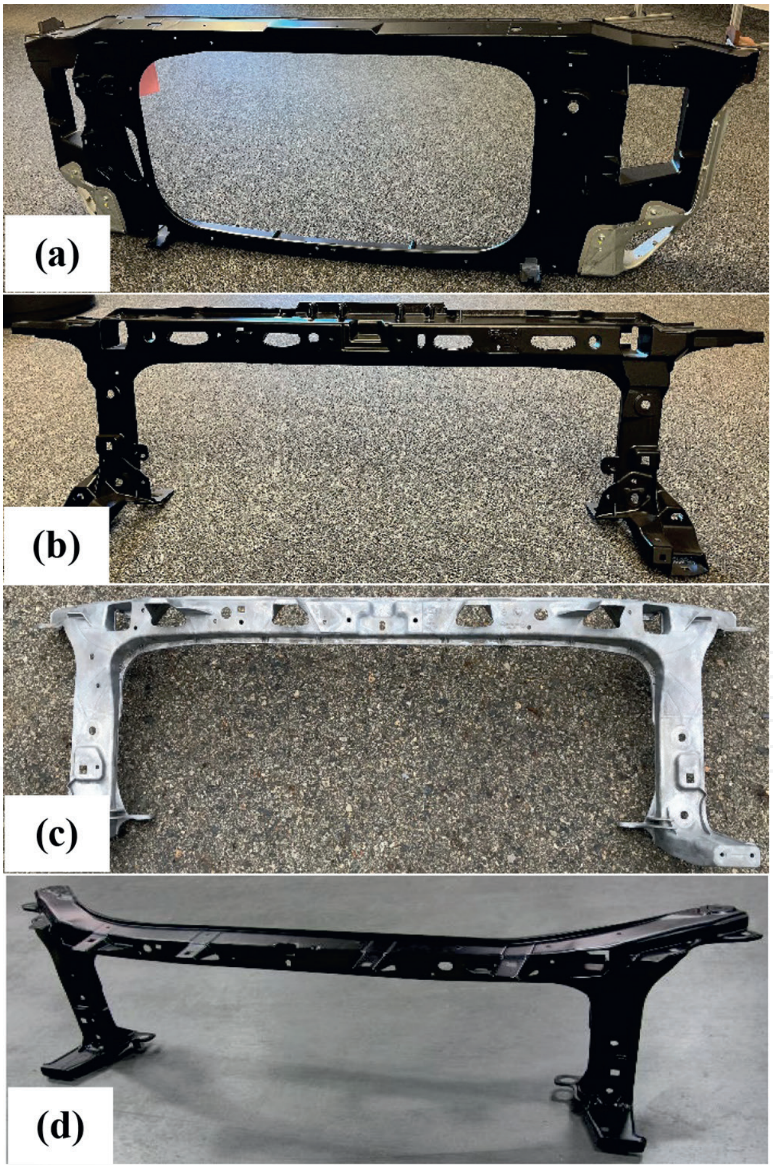

Figure 8.
Evolution of ford F-150 AM50A magnesium radiator support (MRS): (a) 2004 model; (b) 2009 model, (c) and (d) 2017 model before and after coating.

developed including redesigning the casting and brackets, applying chemical conversion coating and powder coating on magnesium, utilizing 5000 series aluminum spacers and nylon-coated bushings to avoid galvanic contact between magnesium and steel and using zinc electroplated fasteners [47]. The MRS casting design was evaluated through extensive component performance tests at Fords Arizona Proving Ground (APG). **Figure 8(b)–(d)** shows the second- and third-generation MRS castings developed in 2009 and 2017. All three generation castings have similar functionalities; however, significant mass reductions were achieved through optimization of material design and nominal wallstock reductions. The first-generation MRS (11.3 kg) saved 35% weight by replacing the original steel front end in 2004, and the third generation resulted in a mass reduction of 75% compared to the original steel design.

The Chrysler Dodge Viper SRT10 front of dash (FOD) launched in 2003 was the largest single piece of magnesium die casting for automotive body structural application [48]. The one-piece AM60B magnesium casting is assembled with three steel stampings to replace 51 individual assembled stamped steel pieces, achieving a weight reduction of 52%. The magnesium FOD implementation provided OEMs and Tier 1 suppliers with design and manufacturing flexibility and was awarded the 2002 Automotive Cast Product IMA Award of Excellence at the 59th Annual World Magnesium Conference.

A spare tire carrier (STC) component is another application of magnesium alloys for body structures implemented in 2006 [49]. A powder coating or over-molding outer layer has been applied on the STC to improve cosmetic corrosion resistance, as well as scratch and UV degradation resistance [50]. **Figure 9** shows the evolution of the Jeep Wrangler STC from 1996 to current model. The STC on 1996 ~ 2006 TJ model was made of three welded stamping steel parts assembled with a thermoplastic center high mounted stop lamp (CHMSL) which has a total weight of 5.3 kg (**Figure 9(a)**) [51]. **Figure 9(b)** shows the first magnesium STC on the 2007 ~ 2018 JK model which achieved a weight reduction of 65% and a cost saving over the previous steel STC [51]. The HPDC process also showed its advantages by integrating the carrier part with the CHMSL part together which further saved assembly and tooling cost. The casting made of AM60B magnesium alloy and a steel tether was added to provide enough strength for rear impact loading. Furthermore, powder coating, plastic washers/isolator and E-coated fasteners were utilized to enhance abrasion and corrosion performance [51].

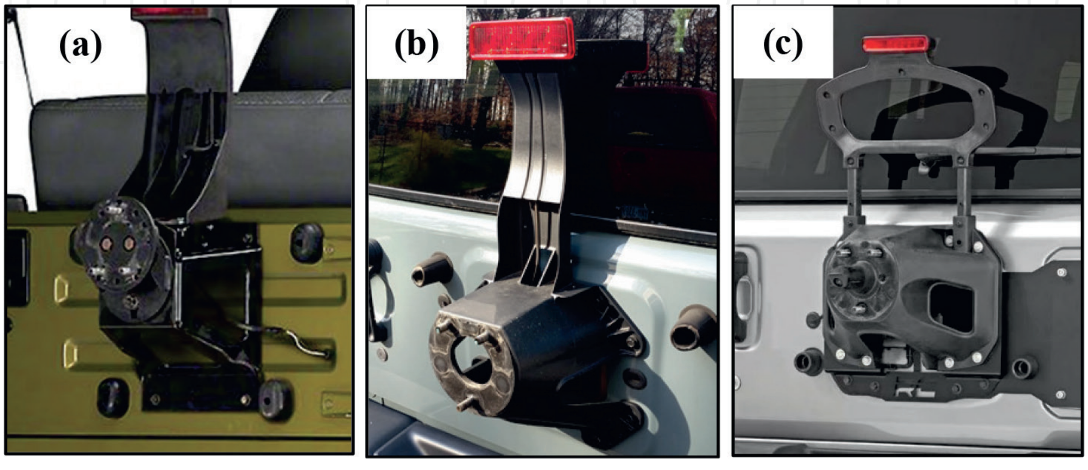

Figure 9.
Evolution of jeep wrangler spare tire carrier (STC): (a) first generation on 1996 ~ 2006 model; (b) second generation on 2007 ~ 2018 model and (c) third generation on 2018 ~ present model.

The STC on 2018 ~ present JL model is made of thixomolding AM60B magnesium alloy with Nylon 66 over molding as shown in **Figure 9(c)** [50]. The STC is designed wider to accommodate two air exhausts and has a weight of 3.1 kg. Although the third-generation STC increases its load capacity from 38 kg to 52 kg over the second generation, it adds an assembly step as a dual post plastic CHMSL, a separate component from the STC.

The first application of magnesium HPDC alloys in liftgate or hatchback inner was reported by Volkswagen Group on a 3 Liter car (3 L/100 km) Lupo TDI in 2000 [52]. The AM50A magnesium alloy inner, cast in a 3300 T die-cast machine was coupled with an aluminum outer to produce an assembly weighing 2.8 kg, resulting in a weight saving of nearly 50% compared to the steel version. Several years later, Mercedes-Benz also developed a HPDC magnesium alloy liftgate inner for the 2009 Mercedes E-class S212 T-model [53]. The 7.1 kg liftgate inner was high-pressure die cast in a 4200 T cast machine using AM50 magnesium alloy. The magnesium liftgate inner (1.4 m × 1.1 m with 2 ~ 5 mm thick) was e-coated and powder coated and then roll seamed and adhesive bonded with an AC170 aluminum outer. The entire assembly achieved 32% mass saving compared to the previous steel design. In the following year, Ford reported the first North American magnesium liftgate inner (1.38 m × 1.315 m) on the 2010 Lincoln MKT which was the largest magnesium liftgate at that time [54–56]. The final casting not only reduced the total weight by 40%, but also improved design flexibility and significantly decreased assembly time by replacing six stamped steel pieces into one integrated casting. The utilization of magnesium as rear gate inner was then significantly expanded [57, 58], and the latest examples are the liftgate inner on 2017 Chrysler Pacifica which achieved a mass reduction of nearly 50% [51, 57] and the 2018 JL swing gate [51].

A magnesium side door inner was firstly reported by Mercedes-Benz on CL-class coupe in 1999 [59] and SL-class in 2000 [60] using HPDC AM50 magnesium alloy. The utilization examples of magnesium cast door inners grown in luxury vehicles are a Ford magnesium door inner prototype project [61], the 2004 Aston Martin DB9 side door inner [62], the 2017 Aston Martin Vanquish S side door inner [58] and the GM integrated side door inner panel R&D project [63]. Some of the latest body structure applications of HPDC magnesium alloys include the door inner upper beltline reinforcement on the 2020 Chevrolet Corvette [63] and a convertible roof top on the 2013 Opel Cascade Cabrio [64].

2.1.3 Powertrain applications

The first utilization of magnesium alloys in the automotive industry was actually for engine piston application in the early 1900s using Dowmetal alloys and was proved to have similar strength and performance as aluminum in the 1921 Indianapolis 500 racing competition [65]. The first die-casting magnesium piston was made by Elektronmetal GmbH (a subsidiary of Mahle GmbH) in 1925 which was manufactured in high-volume applications ranging from commercial vehicle to submarine engines. Magnesium alloys for air-cooled powertrain applications such as pistons, engine blocks and gearboxes were extensively used in the production of the Volkswagen Beetle in 1938 and Transporter in 1949 [66]. However, utilization of magnesium alloy for powertrain applications was reduced due to increasing engine operating temperature and loading in the 1960's when air-cooling engines were replaced with water-cooling. The use of magnesium alloys was restricted due to the corrosion performance of the alloy compositions available at the time and creep performance at the elevated engine operating temperatures. Many efforts were then taken to enhance the corrosion and creep properties of magnesium alloys including limits on impurities in alloy compositions, alloying such as rare earth (RE) element additions [67] and using hybrid designs.

In the last several years, magnesium alloy AZ91D with limits on impurity elements and RE-containing magnesium alloy AE44 have been widely used for powertrain applications. A HPDC AE44 magnesium engine front cover was used for the 2012 Porsche G1 Panamera and 2011 E2 Cayenne models with a weight of approximately 2.1 kg that achieved a 45% weight reduction over the aluminum cover it replaced [45]. A HPDC AE44 oil conduit module was manufactured by GF Casting Solutions and used on the Porsche Panamera as shown in **Figure 10(a)** [68]. The first ever magnesium oil conduit module had a weight of 4.6 kg resulting in a 24% weight saving from the previous aluminum one. **Figure 10(b)** shows the AZ91 gearbox housing utilized on Volkswagen Golf and Passat models which has a weight of 6.8 kg. **Figure 10(c)** and **(d)** shows the AZ91 transfer and transmission cases manufactured by Meridian Lightweight Technologies. Some other powertrain components made by magnesium alloys have also been reported—an AE44 valve cover on the Porsche Panamera, an AJ62 composite crankcase on the BMW 630 Ci [69] and an ACM522 magnesium oil pan used on Honda vehicles [70].

2.1.4 Chassis applications

A HPDC magnesium alloy chassis application was first reported on the 2006 GM Chevrolet Z06 Corvette with an engine cradle application [32, 69, 71]. The engine cradle was made of AE44 magnesium alloy and had a weight of 10.5 kg, resulting in a weight saving of 35% compared to an aluminum design. The magnesium engine cradle was used to support the engine and front bumper beam and functioned as a

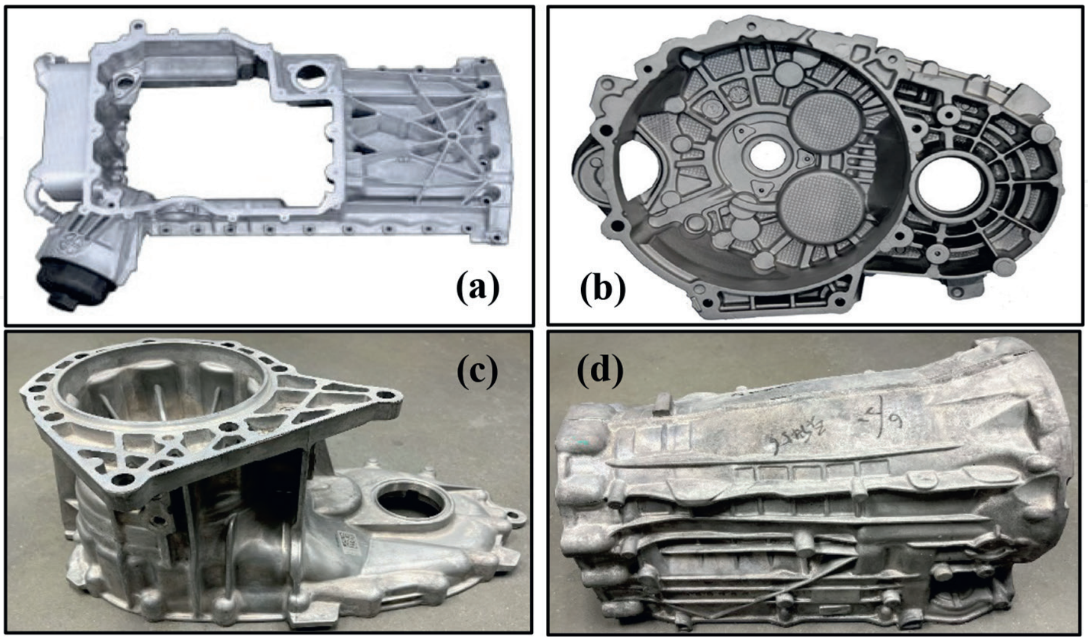

Figure 10.
Powertrain applications of HPDC magnesium alloys: (a) AE44 oil conduit module on Porsche Panamera [48] (courtesy of GF casting solutions) and (b) AZ91 gearbox on Volkswagen golf and Passat [45] (courtesy of GF casting solutions); (c) AZ91 transfer case on ford F-150 and (d) AZ91 transmission case prototype made by Meridian lightweight technologies.

mounting point for several front suspension components. An R&D project demonstrating the feasibility of an HPDC AE44 subframe is another example of magnesium alloys for chassis application [72–74]. The subframe integrated 15 steel stamping parts into a one-piece die casting which had a weight of 15.6 kg that achieved a weight saving of 32%. The subframe connected with other front suspension systems is located underneath the vehicle and is generally exposed to severe corrosive environment conditions such as water, salt and dirt. Therefore, a couple of galvanic corrosion prevention strategies such as aluminum spacers and coated fasteners were investigated through Ford proving ground and lab accelerated corrosion tests [73]. Magnesium wheels are also reported on racing vehicles and roadsters although mainly manufactured through forging process [24, 75, 76]. A die-cast AM60 magnesium wheel was used for the 2015 Yamaha YZF-R1 motorcycle which improved the vehicle maneuverability and handling stability [77]. The advantages and disadvantages of using magnesium automotive wheels were also investigated [78–80]. However, the high cost and corrosion concerns of magnesium alloys restrict their application on automotive wheels. Furthermore, porosity in HPDC components is a safety concern for magnesium cast wheels. The application of HPDC magnesium alloys for automotive chassis application is limited and requires further investigation.

2.1.5 Other automotive applications

Other HPDC magnesium alloy applications in the automotive industry have also been reported. A magnesium AE44 alloy strut tower brace was utilized on the 2020 Ford Mustang Shelby GT500 [81–84]. **Figure 11** shows the evolution of the strut tower brace. The magnesium strut tower brace weighs 3.6 kg and integrates the previous stamped steel and extruded aluminum pieces into one die casting part which achieved a 46% mass reduction. Several coating options were evaluated through Ford's L-467 cyclic corrosion testing (CCT). The resulting production intent coating chosen was a ceramic-based pretreatment and UV-compatible powder coating, while anodized aluminum washers were used for galvanic corrosion prevention [83].

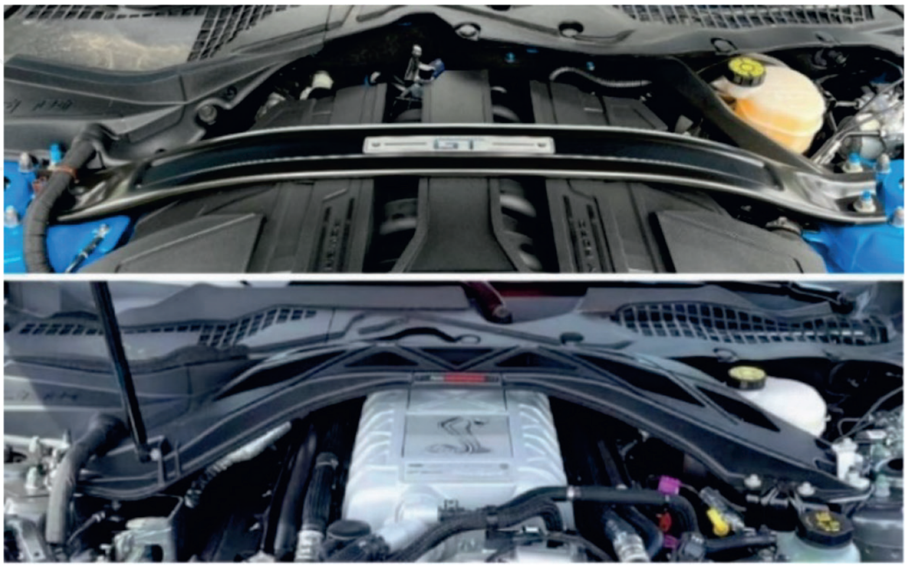

Figure 11.
Evolution of ford mustang GT strut tower mount: (top) steel stamping and aluminum extrusion strut tower mount and (bottom) HPDC magnesium strut tower brace manufactured by Meridian lightweight technologies.

A recent new magnesium die-cast alloy was developed using Mg-Al-Zn-Mn composition which is intended for structural applications [85]. The magnesium alloy chemical composition was tailored to 4 ~ 5% Al and 0.4 ~ 1.2% Zn which demonstrates competitive castability, strength and ductility with conventional AM50 and AM60 magnesium alloys. Other HPDC magnesium automotive applications such as the AM60 JLR Defender driver/passenger side, AM60 JLR left/right hand endcap [45] and 2022 Cadillac CT4-V/CT5-V paddle shifter [86] demonstrate versatile applications in the automotive industry.

2.2 Current EV applications

With recent developments in EV technologies, increasingly more internal combustion engine (ICE) powertrains are being replaced by hybrid, plug-in hybrid and battery electric vehicles. Decreasing the vehicle weight and increasing the battery pack power are two of the primary methods of extending the EV driving range. Therefore, switching existing magnesium components from traditional ICE to EV applications and developing more battery-related magnesium components become significantly important. The majority of HPDC magnesium alloy structural applications are transferrable to EV architectures as much of the body structure of these vehicles is very similar. For instance, an AM60 magnesium CCB is found on Ford's first EV, the 2021 Mustang Mach-E model [87]. An AM60B magnesium front-end carrier was also utilized on the 2013 Tesla Model S sedan, and an AM50 magnesium upper door frame was used on the Tesla Model X made by GF Casting Solutions [88]. The magnesium interior applications like seatback, display bracket, side/back door inner, center console, steering column and many other components are basically same on ICEVs and EVs. Therefore, it is reasonable to expect that more utilizations of those components cast using traditional AM and AZ alloys will be reported.

In newly developed EV-specific applications, an AZ91D onboard charger housing is manufactured by Meridian Lightweight Technologies as shown in **Figure 12(a)** [89–91]. The two-piece magnesium charger housing replaces the previous two-piece aluminum component providing a 25% weight reduction. The charger housing was the first ever HPDC magnesium application in a battery-related component in the EV automotive industry. A prototyped magnesium battery tray is also reported by FUSIUM for automotive applications as shown in **Figure 12(b)** but was not in large-scale production [92].

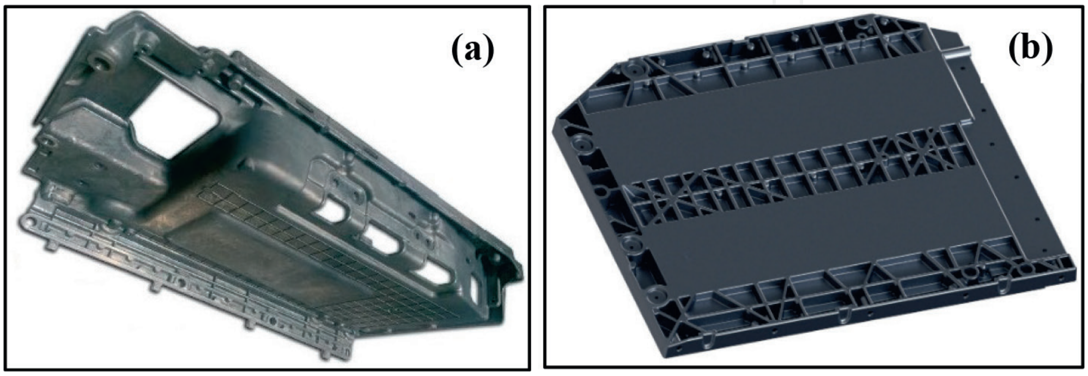

Figure 12.
Battery-related application of magnesium alloys: (a) HPDC AZ91D battery charger housing manufactured by Meridian lightweight technologies [89] and (b) prototyped battery tray [92] (courtesy of Fusium).

Although traditional Mg-Al cast alloys can be utilized to make structural components for EVs, numerous automakers value thermal conductivity properties for battery-related applications. A battery housing application typically requires a lightweight design with the capability for small temperature variations to optimize the battery operations—otherwise known as excellent heat dissipation and thermal conductivity. The conventional cast Mg-Al alloys have relatively low thermal conductivities. **Figure 13** shows the influence of aluminum content of magnesium alloys on the thermal conductivity of magnesium alloys. The experimental thermal conductivities of Mg-Al alloys compare well with the PANDAT simulation results. The addition of RE elements results in improved thermal conductivity compared with the PANDAT predictions aluminum content predictions. For example, DSM-1 alloy developed by Dead Sea Magnesium has a similar thermal conductivity with HPDC aluminum A380 [85]. It is expected that this alloy will have an enormous potential for EV applications owing to its favorable die castability, as well as mechanical and thermal conductivity properties.

Extensive studies and evaluations were conducted to improve the thermal conductivity of traditional Mg-Al alloys through alloying elements like Al [93–96], Zn [94, 97–100], Mn [94, 97], Sn [97, 101], Zr [97], Ca [97, 102, 103], Si [103, 104], Li [101], Sr. [102] and RE elements like Sc [105], Y [106–108], Gd [106, 107, 109], Ce [108, 110–114], La [113, 115, 116], Nd [113, 117] and Sm [108, 113]. The influence of chemical composition, second phase, microstructure, texture and casting processes on the thermal conductivity of magnesium alloys has been discussed in these studies. All alloying elements act to reduce the thermal conductivity from that of pure magnesium. The solute of elements in α-magnesium will distort the original lattice structure, form second phase and act as scattering points for electrons and phonons during thermal transportation. Therefore, the past ways for increasing the thermal conductivity of alloys are mainly focused on minimizing the solute of atoms and fraction of second phase [118]. It was also reported that the thermal conductivity of magnesium alloys is affected by solute

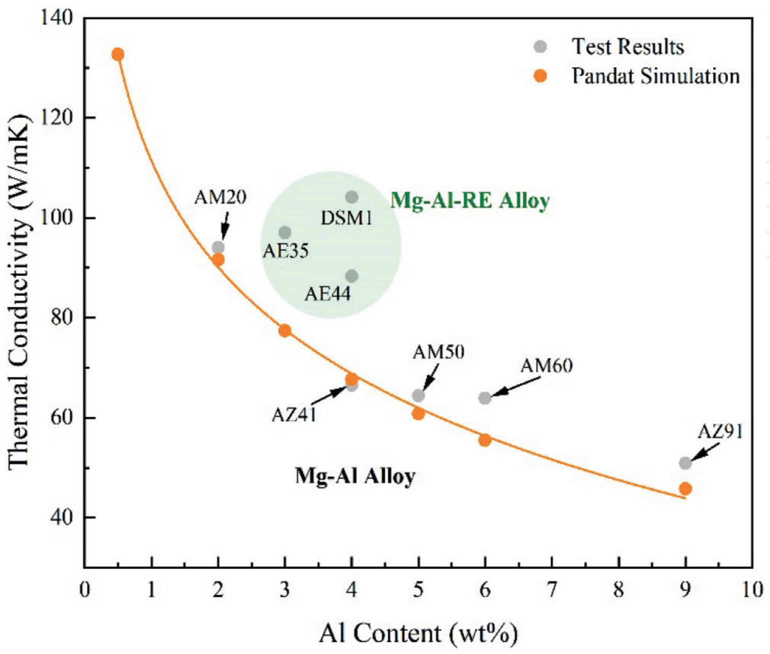

Figure 13.
Influence of aluminum content on thermal conductivity of magnesium alloys: Comparison results from PANDAT simulation and tests on Mg-Al and Mg-Al-RE alloys.

atoms while the second phase only shows very slight effects [108, 109, 117]. Therefore, selecting an alloying element with low solubility in magnesium is critical to improving the thermal conductivity of a magnesium alloy.

Figure 14 shows the solubility of several RE elements in magnesium alloys. The elements La and Ce have relatively low solubility in magnesium and are expected to contribute greater to improving thermal conductivity of a magnesium alloy, e.g., DSM-1. Several other magnesium alloy compositions were also developed using lab scale HPDC machines [119–123] which showed excellent thermal conductivities and good die castability. The Mg-4Al-4Zn-4RE-1Ca magnesium alloy was reported to have good castability for thin-walled components with a thermal conductivity of 94.4 W/mK and desirable mechanical properties (YS = 185 MPa, UTS = 233 MPa and elongation = 4.2%) [121]. The Mg-3RE-0.5Zn alloy is reported to also have good castability, a thermal conductivity of 133.9 W/mK and good mechanical properties (YS = 153 MPa, UTS = 195 MPa and elongation = 4.3%) [122]. Finally, the Mg-4La-2.5Al-0.5Mn alloy with a thermal conductivity of 106.5 W/mK and good strength and ductility (YS = 149 MPa, UTS = 253 MPa and elongation = 11.5%) was reported to have favorable castability as well [103]. However, the evaluation of the castability of these alloys with larger scale die-casting machines is needed upon further consideration in EV applications.

2.3 Aerospace applications

The use of magnesium cast alloys in aerospace applications started as early as the 1930s and peaked two decades later. Several prototype aircrafts were developed containing magnesium, including the XP-56 Black Bullet by Northrop Corporation, with

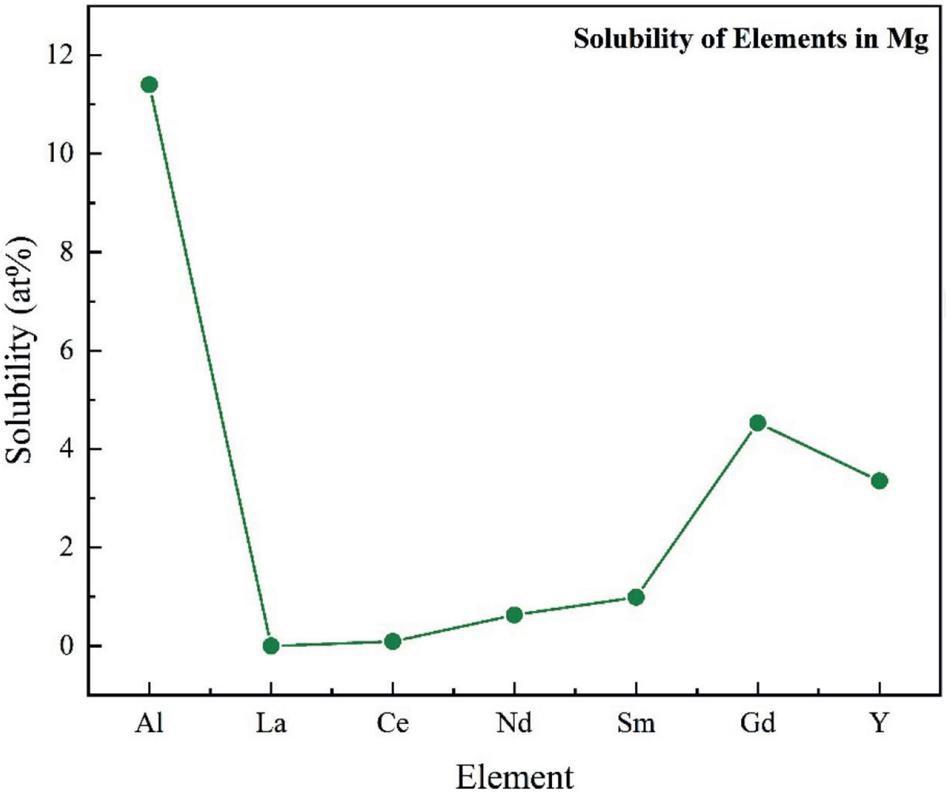

Figure 14.
Solubility of selected RE elements in magnesium [107, 108, 113, 114].

a magnesium airframe and welded skin in 1943, the F-80C (47–171) by Lockheed and the Convair XC-99 by US Air Force [124]. A large volume of magnesium alloy was also found on other aircrafts like the Convair B-36 (~8600 kg), the Boeing B47 (5500 kg), the Soviet Union TU-95MS (1550 kg), the Tupolev TU-134 (780 kg) and the Sikorsky S-56 (115 kg) [125]. Several magnesium cast components were reported on aircrafts, including an AZ92A thrust reverser cascade on the Boeing 737, an EZ33A gearbox on a Rolls Royce and a ZE41 transmission casing on a Sikorsky S92 [124, 126].

However, corrosion and flammability issues restricted further development of magnesium components utilized in the aerospace industry as the use of magnesium components dropped by 95% in mass from the 1966 Tupolev TU-134 to the 1991 TU-304 model [125]. Further, the use of magnesium in aerospace applications was banned in 2005, according to the SAE standard AS8049B. More recently, as the magnesium industry has advanced and with a high demand of lightweighting in the aerospace industry, more attention has been paid to improve the magnesium alloy properties and re-introduce magnesium alloys back into aerospace in the last fifteen years. The Federal Aviation Administration (FAA) developed a flammability standard for magnesium material (FAA Chapter 25) in 2015. As a result, the SAE AS8048 standard was revised to reconsider the use of magnesium alloys in Revision C [127].

Several studies were conducted to improve the flammability resistance of magnesium alloys, mainly through alloying elements such as Al [10, 11], Be [128, 129], Ca [12–19] and REs [130–134]. The addition of Ca and REs are two of the most effective ways of strengthening the magnesium flammability resistance. Minimum addition of REs is well-known to enhance the oxidation resistance of magnesium alloys which can increase their flammability resistance. The FAA completed several tests on the WE43 alloy composition as per Chapter 25 and demonstrated that the flammability characteristics of WE43 were consistent with materials in production and qualified for aircraft interior applications [135]. Some other magnesium alloys that can pass FAA Chapter 25 testing were also reported [136]. However, those alloys are either too expensive or non-castable for large volume production using a HPDC process. Therefore, the focus of the major studies on improving the magnesium flammability resistance was on alloying using Ca which is a more cost-effective and potentially castable solution. The addition of Ca into magnesium alloy was firstly reported in 1911 [137] and was investigated for flammability and ignition resistance in 1924 [14]. Ca can be added to magnesium alloys either through adding pure Ca or calcium compounds like Al_2Ca [138], CaO [139–141] and $Ca(OH)_2$ [142]. The addition of Ca is reported to increase the magnesium flammability resistance through several mechanisms such as increasing the ignition temperature [128, 143], forming more thermal stable second Laves phases [16, 144] and modifying the oxide film [145, 146].

Here, we tested twelve existing magnesium alloys at Meridian Lightweight Technologies which included five Ca-containing alloys and seven non-Ca alloys as per FAA Chapter 25. **Figure 15** shows the testing results with the correlation of mass loss after testing and aluminum content in each alloy. With the additions of calcium above 0.6%, the flammability resistance of magnesium alloys is significantly improved. **Figure 15** also shows the typical cross-section appearance of alloys after FAA testing where the oxide film formed on Ca-containing magnesium alloy is much denser and smoother than the one without Ca.

Increasing the content of Ca is found to negatively affect the castability of magnesium alloys resulting in die sticking, hot tearing, sinks and cold shots [147]. The hot tearing tendency is increased by an elevated precipitation temperature of Al_2Ca addition into AZ91 which affects filling [148]. Ca additions are also reported

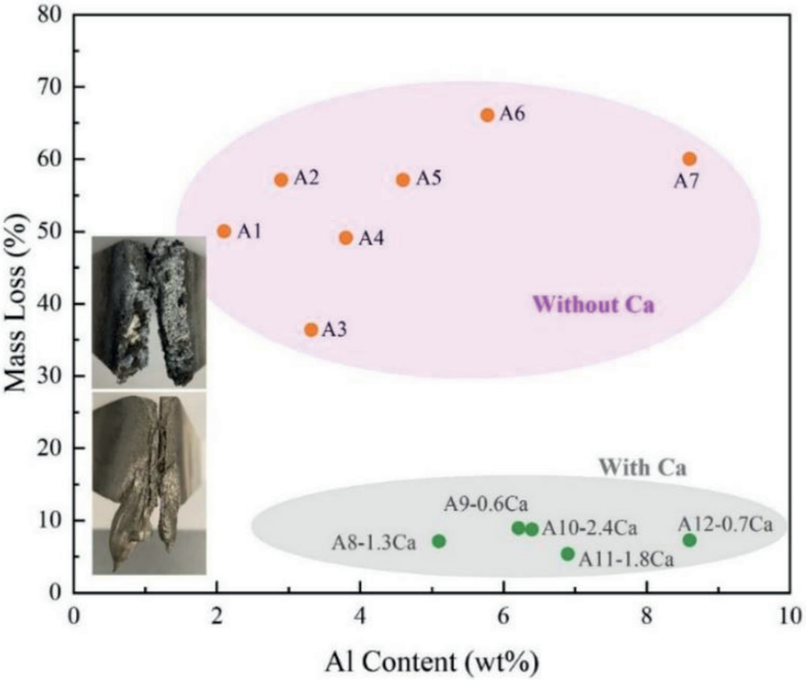

Figure 15.
Influence of alloying on mass loss of magnesium alloys tested as per FAA chapter 25 by Meridian lightweight technologies.

to promote the reaction between die steel and the magnesium melt that results in die sticking [140]. However, Ca-containing magnesium alloys have been reported to have a good combination of flammability resistance and castability through optimization of the alloy composition and casting processes [149–152]. The ZACE05613 magnesium alloy was used to produce transmission cases without hot tearing issues [149]. The Mg-Al-Mn-Ca-Si alloy AMXS6020 was also reported without castability issues [152]. Based on these studies, the development of cast alloys and processes with acceptable flammability resistance is expected to continue with a target for aerospace applications.

3. Conclusions

The applications and developments of HPDC magnesium alloys in the automotive and aerospace industry were reviewed. Attributed to the relatively low density, high strength, good ductility, tunable thermal conductivity as well as extraordinary advantage of greatly decreasing the number of parts and assembly compared to the steel counterparts, HPDC magnesium alloys have been widely used in automotive industry.

HPDC magnesium alloys, e.g., AM50/AM60 have been widely used for interior automotive applications, such as instrument panel (IP), cross-car beam (CCB) and seat frame. They have also been used for automotive body such as roof frames, magnesium radiator support (MRS), front of dash (FOD), spare tire carrier (STC), liftgate or hatchback inners and side door inners.

The powertrain applications of HPDC magnesium alloys started with gearboxes, engine pistons and blocks and were expanded to the use of AZ91D and AE44 which have favorable corrosion and creep properties and are suitable for oil conduits, gearbox house, transfer and transmission cases.

The structural applications of HPDC magnesium alloys are transferrable to EV architectures such as upper door frame and front-end carrier as well as interior applications including seatback, display bracket, side/back door inner, center console, steering column and many other components.

HPDC magnesium alloys also show high potentials for EV-specific applications including onboard charger housing and battery tray. More studies are ongoing to achieve a sweet combination of good castability and thermal conductivity.

The use of HPDC magnesium alloys in aerospace industry has shown prospective potentials with the improvement of the flame resistance of magnesium alloys through alloying elements, e.g., Ca which provides a cost-effective and potentially castable solution.

The future for magnesium alloy applications in these industries, we believe, is quite prospective as evidenced by the development of novel alloy systems combining excellent mechanical properties as well as application-specific tendencies, such as good thermal conductivity or flammability resistance. We foresee a strong market and bright future for magnesium alloys in the automotive as well as aerospace industries.

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