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Full length article

Magnesium casting technology for structural applications

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Abstract

This paper summarizes the melting and casting processes for magnesium alloys. It also reviews the historical development of magnesium castings and their structural uses in the western world since 1921 when Dow began producing magnesium pistons. Magnesium casting technology was well developed during and after World War II, both in gravity sand and permanent mold casting as well as high-pressure die casting, for aerospace, defense and automotive applications. In the last 20 years, most of the development has been focused on thin-wall die casting applications in the automotive industry, taking advantages of the excellent castability of modern magnesium alloys. Recently, the continued expansion of magnesium casting applications into automotive, defense, aerospace, electronics and power tools has led to the diversification of casting processes into vacuum die casting, low-pressure die casting, squeeze casting, lost foam casting, ablation casting as well as semi-solid casting. This paper will also review the historical, current and potential structural use of magnesium with a focus on automotive applications. The technical challenges of magnesium structural applications are also discussed. Increasing worldwide energy demand, environment protection and government regulations will stimulate more applications of lightweight magnesium castings in the next few decades. The development of use of Integrated Computational Materials Engineering (ICME) tools will accelerate the applications of magnesium castings in structural applications.

1. Introduction

Magnesium alloys have some unique solidification characteristics such as excellent fluidity and less susceptibility to hydrogen porosity, and thus, better castability over other cast metals such as aluminum and copper [1]. Casting has been the dominant manufacturing process for magnesium components, representing about 98% of structural applications of magnesium [2].

This paper provides an overview of various processes used for producing magnesium castings. High pressure die casting (HPDC) is the most common method of casting magnesium alloys, and several process variants are being developed for improved casting properties. Gravity sand and permanent mold processes are used to produce high-performance aerospace and defense components. Emerging processes such as low pressure casting, squeeze casting, semi-solid casting, lost foam casting and ablation casting are also discussed. Structural applications of magnesium castings in automotive, aerospace and power tools industries are reviewed in this paper. The opportunities and challenges of magnesium alloys for structural applications are discussed at the end.

2. Melting and melt protection

2.1. Melting

Molten magnesium does not attack iron in the same way as molten aluminum which has high affinity to iron; thus, magnesium alloys can be melted and held in crucibles fabricated from ferrous materials. It is common practice to melt and process molten magnesium in steel crucibles and deliver it to

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casting operations in steel tools and devices. Fig. 1 shows the cross-sectional design of a typical fuel-fired stationary crucible furnace, from which metal for small castings can be hand-poured using ladles [2]. This use of metallic crucibles allows the crucible to be supported from the top by means of a flange, leaving a space below the crucible. The furnace chamber has a base that slopes toward a cleanout door. Modern casting operations generally use electrical furnaces with steel covers and melt transfer devices (a mechanical pump or a heated transfer tube) as shown in Fig. 2.

2.2. Melt protection

Molten magnesium tends to oxidize and burn, unless care is taken to protect its surface against oxidation. Unlike aluminum alloys which tend to form a continuous, impervious oxide skin on the molten bath limiting further oxidation, magnesium alloys form a loose, permeable oxide coating on the molten metal surface. This allows oxygen to pass through and support burning below the oxide at the surface. Protection of the molten alloy using either a flux or a protective gas cover to exclude oxygen is therefore necessary. There are basically two main systems, flux and fluxless, for the melt protection of magnesium alloys.

2.2.1. Flux process

Protecting molten magnesium using flux was developed before proper gaseous protection was developed. A typical flux-melting procedure would be for the crucible with a small quantity of flux (about 1% of charge weight) placed in the bottom, to be preheated to dull red heat [2]. Additional flux is lightly sprinkled onto the melt surface during melt holding and casting operations. Since the discovery of sulfur hexafluoride (SF_6) as effective protective gas for magnesium melting and casting, flux melting is limited to casting of special gravity casting alloys with very high melting points.

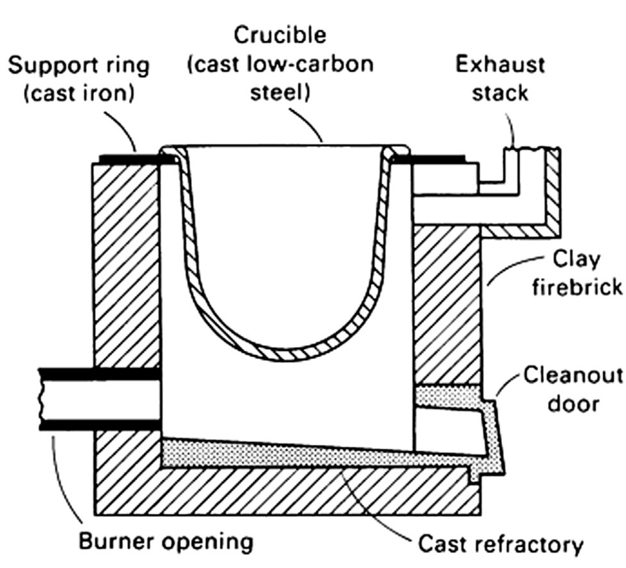


Fig. 1. Cross section of a stationary fuel-fired furnace used for the open crucible melting of magnesium alloys [2].

2.2.2. Fluxless process

Fluxless melting using air/SF_6, air/CO_2/SF_6 or CO_2/SF_6 as protective gas mixtures [3,4] developed in the 1970's was a significant breakthrough in melting, holding, and casting of magnesium alloys. SF_6 has been shown to be an extremely effective oxidation inhibitor for magnesium alloys. The precise mechanism is still not very clear, but simplistically it involves the enhancement of the natural oxide film with MgF_2 to make it more protective with the following possible reactions:

$$2Mg(l) + O_2 \rightarrow 2MgO(s) \quad (1)$$

$$2Mg(l) + O_2 + SF_6 \rightarrow 2MgF_2(s) + SO_2F_2 \quad (2)$$

$$2MgO(s) + SF_6 \rightarrow 2MgF_2 + SO_2F_2 \quad (3)$$

MgF_2 tends to block the pores in the MgO film and make it more protective [5]. The fluxless process using non-toxic SF_6 protective became immediately accepted by both the ingot producers and the die casting sections of the foundry industry, because of its improved melt efficiency and elimination of flux inclusions in the castings. The new melting process was next extended to the sand casting process.

However, SF_6 has a global warming potential approximately 24,000 times that of CO_2, in addition to a very long retention in the atmosphere (3200 years), which means that emission of 1 kg SF_6 is equivalent to that of 26.5 MT CO_2 [5]. Alternative protective gases such as HFC134a, HFE7100 and NovacTM612 have been developed in recent years. While HFC134a and HFE7100 still have significant GWP's, they are both significantly lower than that of SF_6 and greenhouse emissions could be reduced by up to 98% compared to SF_6 by immediate replacement. Most promising is NovacTM612 with GWP equivalent to CO_2, but further development is required to optimize the use of this material in production applications. Significant utilization of these alternatives is expected due to the increasing government regulation and environment protection.

3. High pressure die casting

High pressure die casting (HPDC) offers attractive flexibility in design and manufacturing of light metals components. The excellent die filling characteristics of magnesium alloys allow large, thin-walled and complex castings to be economically produced by this process, replacing steel structures made of numerous stampings and weldments. Table 1 lists some design parameters and manufacturing characteristics for magnesium and aluminum die castings [3]. Magnesium die castings can be designed with thin walls in areas where strength is not a concern and with thicker walls in areas where strength requirements are higher. Magnesium can be cast with thinner walls (1–1.5 mm) compared to aluminum

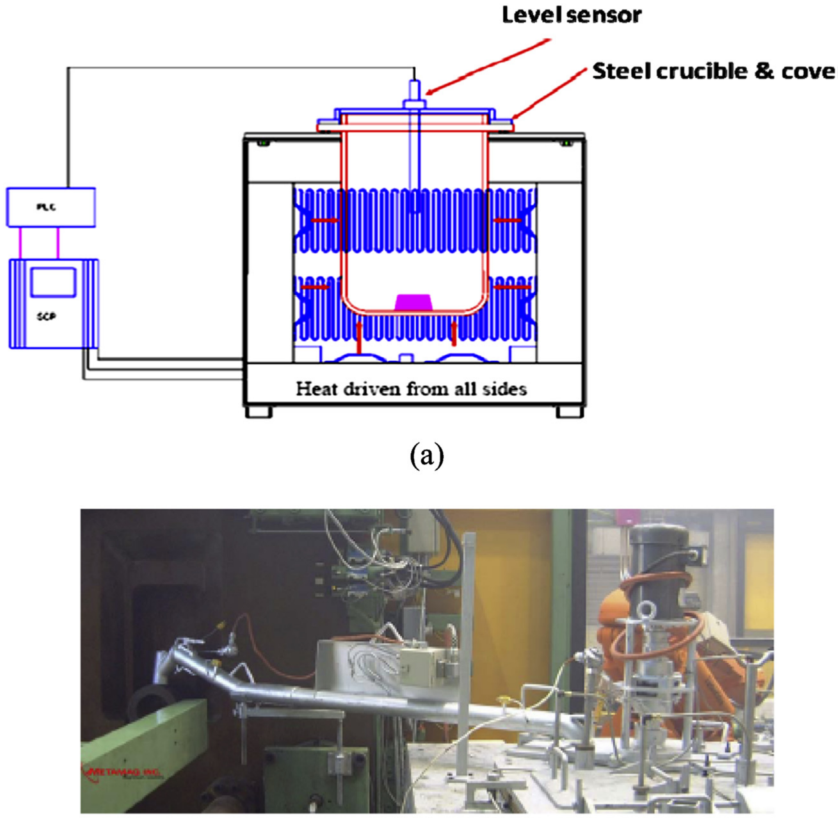


Fig. 2. (a) Modern electrical furnace with a steel cover; and (b) metal transfer tube delivering molten magnesium to a die casting machine (Courtesy of Metamag, Inc., Strathroy, ON, Canada).

(2—2.5 mm). The stiffness disadvantage of magnesium vs. aluminum can be compensated with appropriately located ribs without increasing the wall thickness. Compared to aluminum, magnesium has a lower latent heat for solidification and less affinity to iron in steel tooling, which leads to considerably shorter casting cycle times and longer die lives in die casting operations. Table 1 also shows that magnesium offers additional advantages in machinability compared to aluminum (Table 2).

There are basically two types of high pressure die casting processes: hot chamber die casting and cold chamber die casting.

3.1. Hot chamber die casting

The hot chamber die casting process is illustrated in Fig. 3 [8]. In the hot chamber die casting method, the molten metal is held in an enclosed steel crucible, under a protective atmosphere. A valve allows a controlled volume of molten metal into the gooseneck that is immersed in the molten metal. A plunger injects this metal into the cavity of the die through a nozzle. To prevent freezing of the metal, the nozzle is heated to 400—500 °C with gas, electric or by induction heating.

The nozzle is often kept full with molten metal between the shots to shorten cycle time. Hot chamber die casting offers some distinct advantages in casting magnesium. First and

Table 1
Comparison of design parameters and manufacturing characteristics for magnesium and aluminum die casting [7].

Material	Mg die casting	Al die casting
Dimensional tolerance (mm/mm)	±0.001	±0.002
Draft angle (°)	0—1.5	2—3
Minimum wall thickness (mm)	1—1.5	2—2.5
Casting/molding cycle time (unit)	1.0—1.4	1.4—1.6
Typical die life (×1000 shots)	250—300	100—150
Trimming cycle time (unit)	1	1
Machinability	Excellent	Good
Welding/joining	Fair	Good
Surface finishing	Excellent	Excellent
Recyclability	Good	Good

Table 2
Comparison of conventional HPDC, vacuum-assisted HPDC and super vacuum die casting.

Process	Conventional HPDC	Vacuum-assisted HPDC	Super-vacuum die casting
Vacuum level	None	60—300 mbar	<60 mbar
Advanced vacuum monitoring and controls	No	No	Yes
Sealed die surfaces	No	Yes	Yes
Susceptibility to gas porosity	High	Low	Very low
Heat treatable	No	Yes	Yes

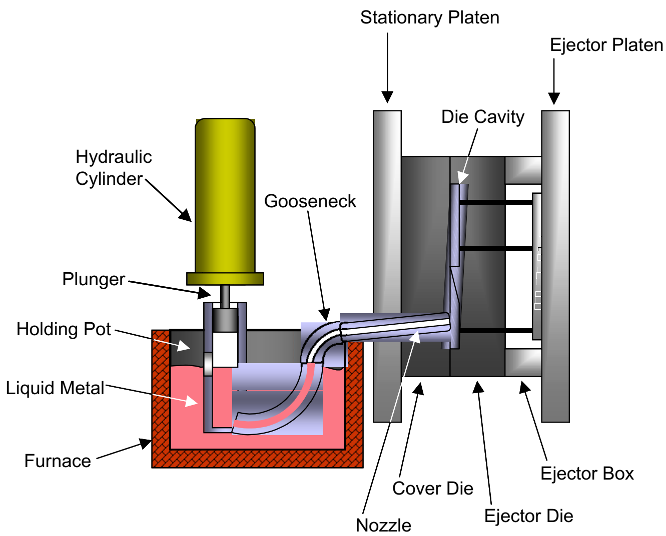


Fig. 3. Schematics of hot chamber die casting [8].

foremost, it limits the contact of the molten metal with air thereby reducing or eliminating the formation of oxides. Until it enters the die cavity, the metal is contained in a sealed melting crucible and is protected by a cover gas. Hot chamber die casting takes advantage of the compatibility of magnesium with steel. In contrast to molten aluminum that attacks steel and cannot be contained in steel vessels, magnesium is "steel friendly". Consequently, most magnesium melting crucibles and transfer ladles are usually made of carbon steel. When higher strength is required, 400 series stainless steels can be used. However, the nickel and cobalt containing 300 series stainless steels are not recommended. These elements, when dissolved in magnesium alloys, even in ppm levels, are detrimental to their corrosion resistance.

The pressure applied on the molten metal during injection is lower than in cold chamber die casting, and limits the size of parts made by the hot chamber method. The main reason is the high operating temperature of various components, such as the nozzle, that limits the pressures that can be applied. A typical 400 tons magnesium hot chamber machine makes parts that weigh up to 2.5 kg. It has a clamping force of 400 tons, and applies about 35 MPa maximum pressure on the metal. Due to the short cycle time (up to six parts per minute), the hot chamber die casting process is very competitive for small parts. Typical magnesium parts made by the hot chamber die casting method are shown in Fig. 4, which include small automotive pasts (e.g., steering wheel, steering column and airbag housing), 3C products (e.g., cases for cell phone, laptop and LCD projector) and power tools.

3.2. Cold chamber die casting

The cold chamber die casting process is shown in Fig. 5 [8]. The molten magnesium is fed into a shot cylinder either by hand ladling, auto-ladling, or by a pump. It is then injected fast (5—10 m/s) by a plunger into the cavity, where it solidifies into a net shape part under high pressure (35—140 MPa). If used to form undercuts, cores are retracted. Finally, the casting is ejected, and the part is trimmed by separating it from the

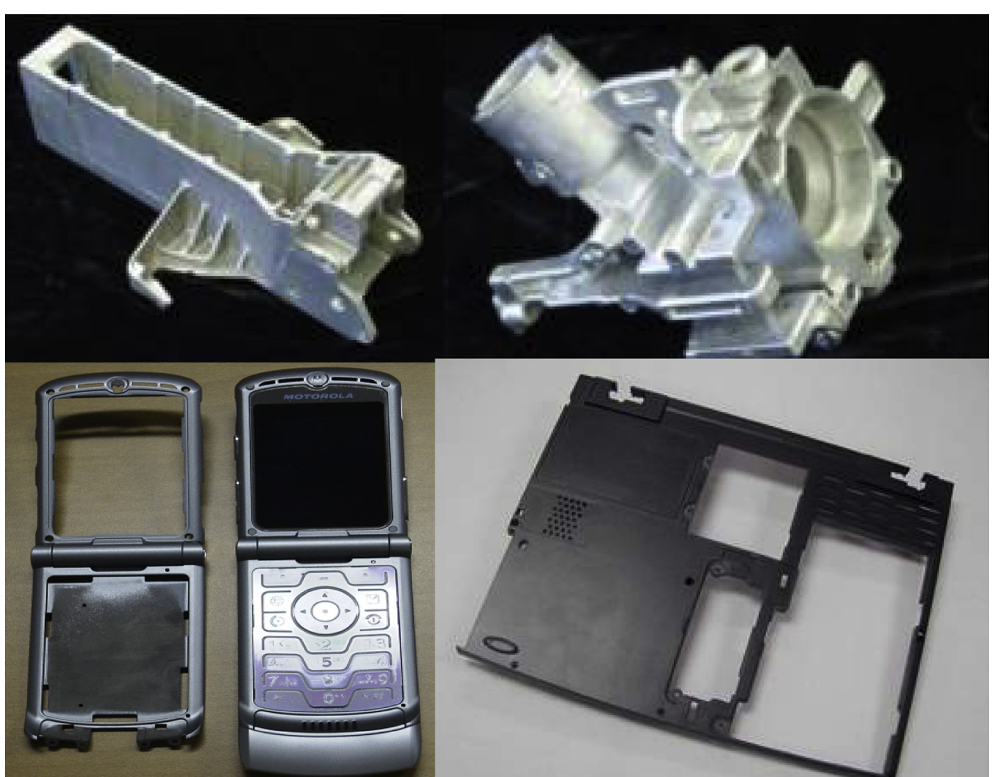


Fig. 4. Typical magnesium parts made by hot chamber die casting process (Courtesy of Contech US, LLC and Foxconn Technology Group, China).

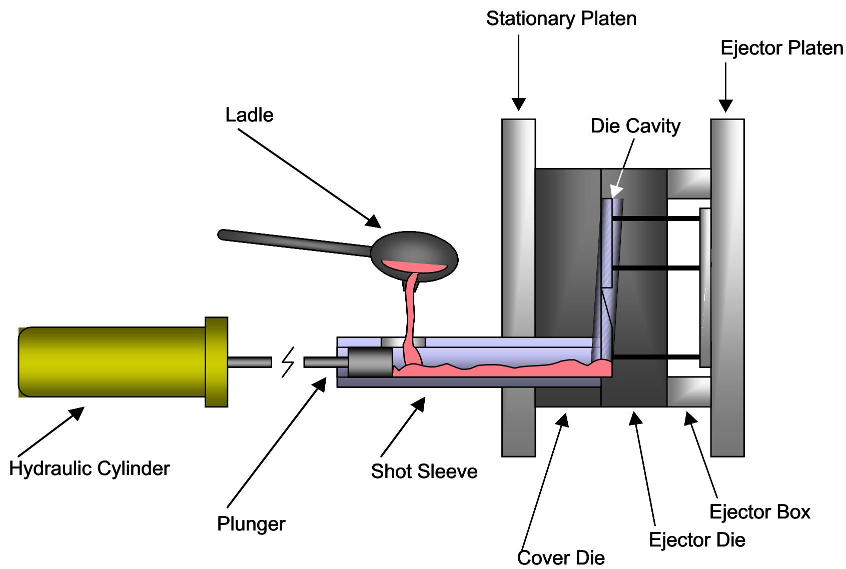


Fig. 5. Schematics of cold chamber die casting [8].

gating system and the biscuit. The entire cycle takes usually around 1 min.

The cold chamber die casting process offers a number of distinct advantages in the casting of magnesium:

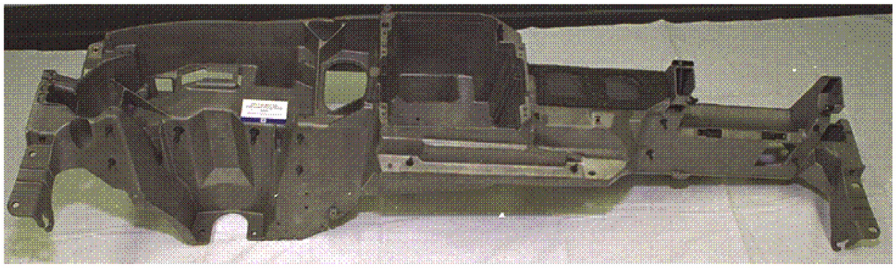
- As a high volume, net-shape process, it is very cost effective in the highly competitive automotive and electronics industries;
- The short cycle time limits the contact time of molten magnesium with the dies, minimizing the chance of reaction with the die material and the air;
- In contrast to molten aluminum that tends to interact with steel, molten magnesium can be contained and handled with steel tools;
- The fast injection and filling of the molten metal into the die cavity allows fabrication of large parts with very thin sections (e.g., 1—1.5 mm);
- The rapid solidification rates (100—500 °C/s depending on cross section) result in very fine grains especially in the skins; and
- Magnesium alloys have lower specific heat than aluminum. As a result, H13 tool steel dies last at least twice as long dies used to cast identical aluminum parts.

Most automotive magnesium die castings are produced by the cold chamber die casting process due to the above advantages. Typical parts include instrument panel beam, radiator support, engine cradle, seat frame, engine block, transmission case and oil pan. Fig. 6(a) is the first high-volume one-piece die cast magnesium instrument panel (IP) beam introduced in 1996 by General Motors (GM) for its full-size van (GMC Savana and Chevrolet Express). A 12.3-kg part with a nominal thickness of 4 mm, this was the world's largest magnesium die casting, which provided 32% mass saving compared to the steel design and significant performance improvements (improved crashworthiness and reduced vibration) and cost savings due to parts consolidation (25 parts in the magnesium design vs. 67 parts in steel) [9]. The advance of the magnesium die casting technology in the last decade has resulted in more efficient IP designs in recent GM models achieving even greater mass savings (40—45%) and part consolidation. Fig. 6(b) shows a 6.9-kg magnesium IP beam casting for Buick LaCrosse.

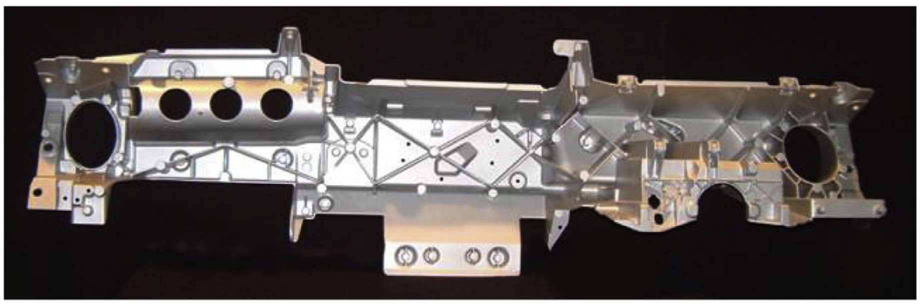
3.3. Vacuum die casting

Despite the high productivity, the biggest drawback of the conventional high-pressure die casting process (magnesium or aluminum) is the high porosity level due to entrapped gases resulting from the injection of molten metal at very high velocities during die casting. The porosity issue is less serious for thin-wall sections (<2.5 mm) where the mechanical properties are largely provided by the fine-grained and pore-free casting skins. When thicker walls are needed for stiffness and/or durability in critical structural applications, the effect of porosity on mechanical properties (especially ductility and fatigue strength) is more serious. The following alternative processes can produce castings with less porosity, but often at higher costs or lower productivity.

Vacuum die casting is an innovative process, where the reduced pressure created in the injection chamber and die cavity just prior to injection, leaves no entrapped air in the casting, and enables the manufacturing of relatively large thin wall castings with significantly improved properties. Castings produced with this process are currently targeted for components require pressure tightness and good mechanical properties via heat treatment. Vacuum die casting thus stretches the capabilities of conventional die casting while preserving its economic benefits [8]. Vacuum die casting of aluminum alloys is very popular in North America, with over 20% of all die casters having vacuum die casting capabilities [10].



(a) One-piece instrument panel beam for GMC Savana and Chevrolet Express (12.3 kg).



(b) Current generation instrumental panel beam for Buick LaCrosse (6.9 kg).

Fig. 6. General Motors magnesium instrument panel beams made by cold chamber die casting.

3.3.1. Vacuum-assisted die casting

While vacuum die casting of aluminum is widely practiced, there is only one company in North America, Gibbs Die Casting (Henderson, KY), that uses vacuum for die casting magnesium components. Fig. 7 shows the Gibbs vacuum-assisted vertical die casting process [11]. In this process, a vacuum instantaneously evacuates all air from the cavities and feed channels. This vacuum begins drawing the molten magnesium through the transfer tube into the injection cylinder. In 2 s or less, the desired amount of molten alloy is drawn from the center of the melt, through the transfer tube, and into the injection cylinder. The first movement of the plunger shuts off the metal flow from the feed tube to control the amount of metal ladled. The molten alloy is then smoothly injected into the air-free die cavities while the vacuum remains active, thus avoiding any air pockets and resistance to metal fill. Then high pressure is brought to bear on the freezing metal, while the vacuum remains active. After an appropriate dwell time, the die opens and the part is automatically ejected onto a shuttle tray for transfer out of the die area.

A simple vacuum system can be used in vacuum-assisted horizontal die casting process, and is sufficient in reducing gas porosity in magnesium castings [12]. Conventional HPDC parts are not heat-treatable due to the formation of blisters upon heating to solutionizing temperatures when entrapped air in porosity expands. The reduced gas porosity in vacuum-assisted die casting can be heat-treated without blisters. Extensive blisters were observed on the surfaces of conventional die cast parts after heat treatment, while no blisters were observed on the surfaces of the vacuum-assisted castings.

3.3.2. Super vacuum die casting

Advanced vacuum monitoring systems have been developed in recent years to achieve higher vacuum levels and to assess the vacuum level throughout the entire filling process and ensure the system is functioning properly in die casting of aluminum and magnesium. High vacuum die casting process, such as Alcan's patented High-Q-Cast process, has been used in high-volume aluminum casting production of automotive body parts such as the Audi A2 B-pillar. New aluminum alloys, such as AURAL-2 and Magsimal 59, have been specifically developed for the high vacuum die casting processes [13,14].

Similar to high vacuum die casting process for aluminum, a super vacuum die casting (SVDC) process has been developed for magnesium alloys, which uses a powerful vacuum system, advanced vacuum controls and monitoring systems, and unique die/gating system designs [15]. Table 3 shows the tensile properties of as-cast SVDC shock tower castings compared to HPDC components of similar sizes [15]. Although SVDC provides limited improvement in yield strength, which is primarily determined by the alloy chemistry and grain size; the ductility and ultimate tensile strength of the SVDC castings for both AZ91D and AM60B alloys are significantly improved compared to the conventional HPDC properties due to the reduced porosity in these castings.

4. Gravity casting

Although the current production of magnesium parts is dominated by HPDC process due to its high productivity and the superb die-castability of magnesium alloys, gravity sand and permanent mold castings are used in a variety of structural applications.

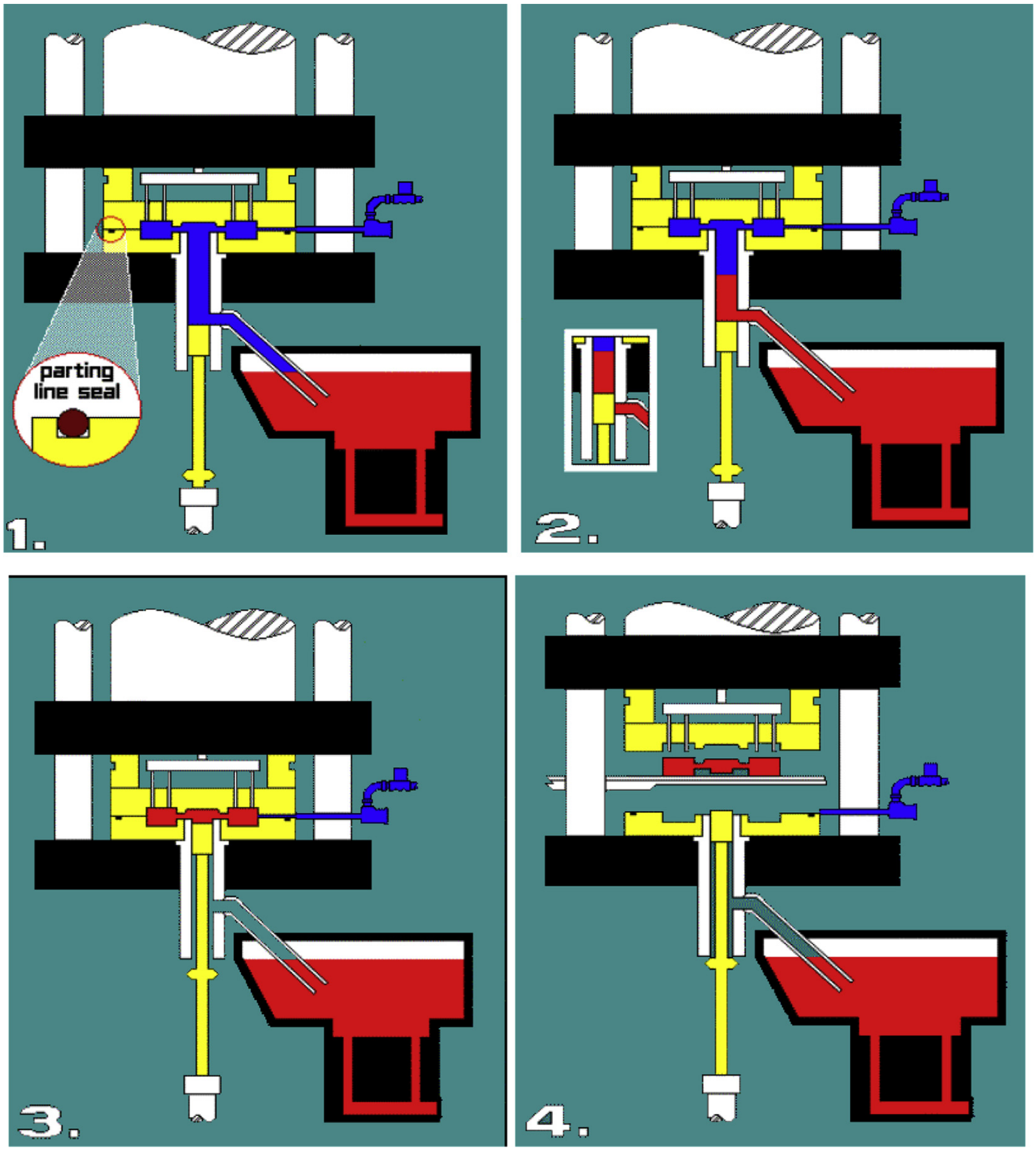


Fig. 7. Gibbs vertical vacuum assisted die casting process (Courtesy of Gibbs Die Casting, Henderson, KY, USA [11]).

4.1. Sand casting

A wide range of magnesium castings weighing up to 1400 kg can be produced using sand casting processes (green sand, CO_2/silicate or resin-bonded sand) [2]. Sand casting (SC) of magnesium alloys is very similar to other cast metals except that suitable inhibitors need to be used in the molding and core sand mixtures to prevent the metal-mold/core reactions. These inhibitors include the following, used singly or in combination: sulfur, boric acid, potassium fluoroborate, and ammonium fluorosilicate [2]. Low-cost wooden pattern equipment is normally used for general purpose castings. However, metal or plastic pattern and core-box tooling fabricated by precision manufacturing is used to produce magnesium castings with high level of dimensional quality. Due to the pronounced oxidation tendency and the low density of molten magnesium, the gating and runner system needs to be designed to minimize the turbulent flow and ensure sequential solidification of magnesium castings.

Table 3
Tensile properties of as-cast SVDC shock tower castings compared to HPDC components of similar sizes [15].

Alloy	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %
AZ91D-SVDC	158.7	227.7	3.6
AZ91D-HPDC	150	200	2.5
AM60B-SVDC	123.7	226.6	9.1
AM60B-HPDC	120	210	6.0

4.2. Permanent mold casting

The permanent mold casting (PMC) is similar to sand casting but difference is that it uses a metal mold. There are two main types of permanent mold casting processes, depending on whether metal cores (per-mold) or destructible sand cores (semi-permanent mold) are used. Compared to sand casting, there are numerous advantages of the permanent mold casting including better surface finish, precise and consistent dimensional control and improved mechanical properties due to faster solidification. However, there are also practical limitations on the intricacy of shapes that can be cast in PMC process. Several factors affecting the quality of permanent mold casting of magnesium have been studied [16] and summarized as follows:

- Purging the mold with cover gas (such as CO_2/SF_6) prior to pouring can make it free of oxygen and improve the casting quality.
- C_2Cl_6 tablet is an effective degassing agent in magnesium casting.
- Adding fluorinated compound such as NaF to permanent mold coating can improve the casting quality due to the formation of MgF_2 reducing the oxidation in the metal–mold interface.
- Due to the relatively low melting points of magnesium alloys, cast iron can be used as die material for low volume production while H13 tool steel dies are preferred for high volume production.
- Alloys prone to hot tearing tend to be those with wide freezing ranges and/or little eutectic content that cannot completely surround the grains. Fine grain-size promotes good interdendritic feeding, lower interlocking stresses and hot tear healing. High surface tension of the interdendritic liquid which impedes interdendritic channel healing would increase hot-tear resistance.
- Oxide inclusions impede interdendritic feeding and reduce the wettability of the interdendritic fluid thereby having an adverse effect on hot-tear tendency.

5. Low pressure casting

Fig. 8 shows a schematic diagram of a typical low pressure casting (LPC) machine [17], using sand or permanent molds, i.e., low pressure sand casting (LPSC) or low pressure die casting (LPDC). An LPC machine usually includes a pressurized crucible located below the mold table with a feed tube (riser tube) running from the crucible to the bottom of the mold. As shown in Fig. 8, dry gas is used to pressurize the surface of the molten metal in the crucible with relatively low pressure sufficient to overcome the difference between the die and the surface of the molten metal in the crucible, and to force the molten metal to rise through the feed tube, feeder and gating system into the die cavity. When the mold cavity is filled, the exerting pressure is increased to continue feeding metal into the risers to compensate for shrinkage of the casting during solidification. The external pressure is released after the casting has completely solidified. With proper design of the feeding system, the metal in the feed tube is still molten, and flows back into the crucible. The total cycle is repeated for the next casting. Since a quiescent fill and design of complex internal passages are possible, the solidified casting can be virtually free of internal porosity.

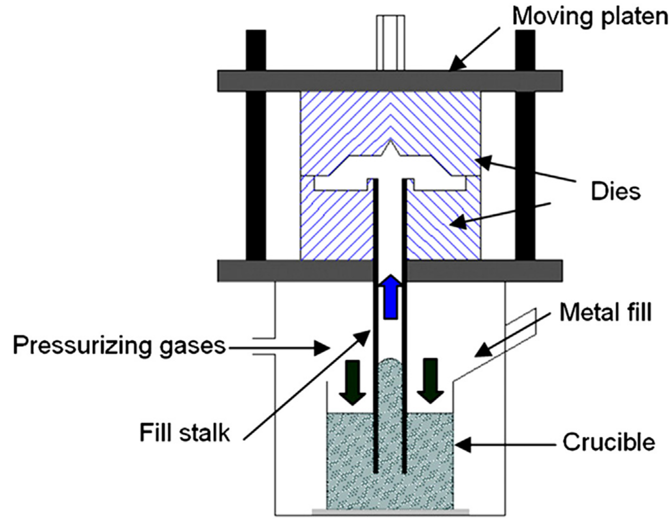


Fig. 8. A schematic diagram of a typical low pressure casting machine [17].

Although the LPC process is associated with lower capital investment compared to the HPDC process, it cannot produce wall thicknesses below 4 mm for aluminum or 3 mm for magnesium, and is also associated with a longer cycle time; about 2–4 times longer compared to HPDC depending on the part complexity. However, the LPC process can produce hollow castings that cannot be produced by the HPDC process. Hollow castings are desirable since they provide efficient structures from the boxed sections they can provide.

While LPC is well established for aluminum, this is not the case for magnesium alloys. LPC of magnesium alloys has been a subject of some recent studies [17–20]. Fig. 9 is a prototype magnesium control arm made by GM using low pressure die casting (LPDC) process. Table 4 compares the mechanical properties of AZ91 and AM50 castings of similar thicknesses of ~10 mm produced by LPDC, gravity permanent mold cast (PMC) and high pressure die casting processes [20]. The results suggest that the LPDC castings showed improved properties compared to similar thickness castings that can be made with the gravity process, mostly due to controlled casting filling with the application of pressure and lower porosity due to the application of pressure during the

Fig. 9. A prototype magnesium control arm made by GM using low pressure die casting process.

Table 4
Tensile properties of low pressure die casting (LPDC) AZ91 and AM50 samples compared to gravity permanent mold cast (GPMC) and high pressure die cast samples of similar thicknesses of ~10 mm [20].

Alloy	Casting	Temper	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %
AZ91	LPDC	As-cast	92.2	180.4	3.4
AZ91	LPDC	T4	76.9	218.5	6.6
AZ91	LPDC	T6	138.2	228.1	1.7
AZ91	GPMC	As-cast	82.7	178.4	3.9
AZ91	HPDC	As-cast	110–130	130–175	0–1
AM50	LPDC	As-cast	57.8	192.3	8.7
AM50	LPDC	T4	68.3	210.6	9.5
AM50	LPDC	T6	66.4	200.3	8.6
AM50	GPMC	As-cast	53	173.4	8.1
AM50	HPDC	As-cast	102–122	132–215	0–5

entire solidification process, and LPDC is a preferred process to produce thick-wall magnesium castings (~10 mm thick) that cannot be produced by the high pressure die casting (HPDC) process without porosity. The LPC parts are also heat-treatable and a T6 heat treatment (18 h at 420 °C, hot-water quench and 16 h at 175 °C) can improve the yield and ultimate strength of LPDC AZ91 castings by about 50% and 24%, respectively, but with a reduction in elongation. The age-hardening effect in AZ91 alloy is due to precipitation of $Mg_{17}Al_{12}$ phase in the microstructure [20]. Due to its lower aluminum content, AM50 alloy does not show any significant age-hardening effect upon heat treatment. However, the grain size in LPDC castings an order of magnitude larger compared to HPDC castings, due to the faster cooling rate in the latter, which also translates into higher yield strength in the HPDC castings. Grain refinement is needed in the LPDC process to improve the strength while maintaining its superior ductility.

6. Other casting processes

6.1. Thixomolding

Thixomolding is a semi-solid process producing near net-shape magnesium parts. As shown in Fig. 10, the process consists of introducing magnesium alloy feedstock in the form of metal granules at room temperature into a heated barrel and screw of a modified injection molding machine, and then raising the temperature of the material to a semi-solid region under high shear rate mixing [21]. The semi-solid slurry, consisting of nearly spherical solid particles suspended in a liquid matrix, is then injected into a preheated metal mold to make a net shape part. Similar to vacuum die casting, this process results in less porosity and improved fatigue strength over conventional die casting [21]. The thin wall capability (0.5–1 mm) and the similarity with plastic injection molding process have resulted in successful applications of magnesium Thixomolding in computer and electronics industries (casing applications for cell phones, cameras and computers). However, the higher costs associated with magnesium granules (feedstock for Thixomolding), and the lack of large size molding machines, have hindered the automotive applications of this process.

6.2. Squeeze casting

There are two types of squeeze casting processes: direct and indirect squeeze casting. In both types of the processes, molten metal is introduced to casting cavities with minimum turbulence and solidifies under very high pressure (typically above 100 MPa) within closed dies.

6.2.1. Direct squeeze casting

Direct squeeze casting (DSC) is also termed liquid metal forging. As shown in Fig. 11, the direct squeeze casting process consists of metering liquid metal into a preheated, lubricated die and forging the metal while it solidifies [8]. The pressure is applied shortly after the metal begins to freeze and is maintained until the entire casting has solidified. Casting ejection and handling are done in much the same way as in closed die forging.

6.2.2. Indirect squeeze casting

While direct squeeze casting is generally performed on a vertical machine (similar to a forging press), indirect squeeze casting (ISC) is more akin to conventional high pressure die casting, using both vertical or horizontal machines. During an indirect squeeze casting such as the "Horizontal Vertical

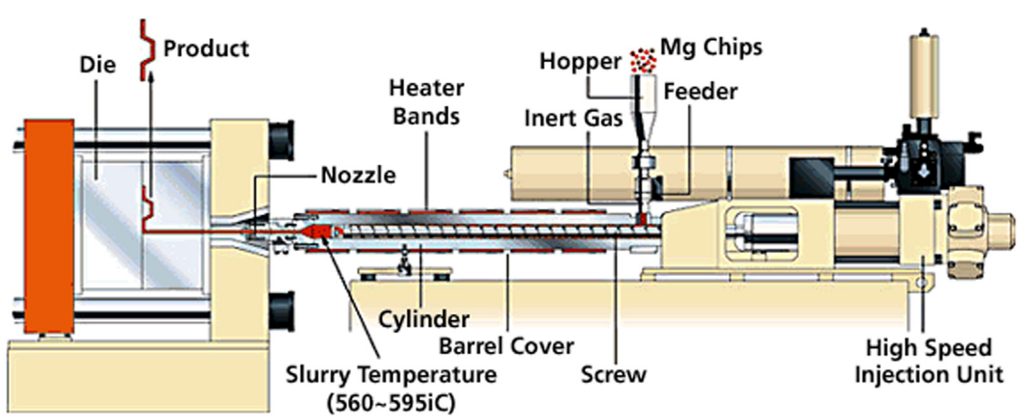


Fig. 10. A schematic diagram of a Thixomolding machine [21].

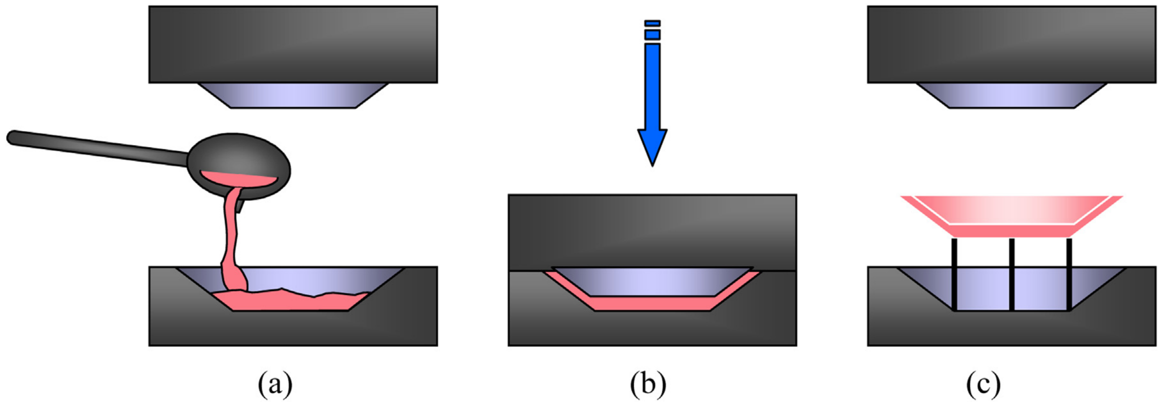


Fig. 11. Schematic illustrating direct squeeze casting process operations: (a) melt into die cavity; (b) close tooling, solidify melt under pressure; and (c) eject casting [8].

Squeeze Cast" (HVSC) process [22], molten magnesium is transferred (preferably in an enclosed tube) to the shot sleeve, and then injected into the die cavity through relatively large gates and at relatively low velocity (usually under 0.5 m/s). Melt in the die cavity is then solidified under high pressure "indirectly" applied by the plunger through the large gating system. Fig. 12 compares the metal flow in conventional die casting and indirect squeeze casting process [8]. The reduced inject speed in the ISC process promotes the planar filling of the metal front within the die cavity, and thus eliminating entrapped gases in the castings.

The absence of turbulent metal flow, aided by the high applied pressure, can suppress gas porosity in both DSC and ISC castings. The tendency toward shrinkage porosity is also reduced by using a bare minimum of superheat in the melt during casting. This is possible in squeeze casting because melt fluidity, which requires high casting temperatures, is not necessary for die fill, the latter being readily achieved by the high pressure applied. In heavy sections of the casting, which are particularly prone to the incidence of shrinkage porosity, the applied pressure squirts liquid or semi-liquid metal from hot spots into incipient shrinkage pores to prevent pores from forming. Alloys with wide freezing ranges accommodate this form of melt movement very well, resulting in sound castings with a minimum of applied pressure.

Table 5 compares the tensile properties of indirect squeeze casting (ISC) AZ91 samples compared to gravity permanent mold cast (GPMC) and high pressure die cast (HPDC) samples of similar thicknesses of ∼10 mm [20,24]. Compared to GPMC or LPDC samples (Table 4), the squeeze castings show improved strength and ductility, due to the applied high pressure which ensures intimate contact between melt and die and thus increased cooling rates during solidification. Therefore, squeeze casting provides a good alternative for making thick-wall castings in magnesium.

6.3. Lost foam casting

The lost foam casting (LFC) process consists of two steps: Firstly, placing a molded and refractory-coated polystyrene foam pattern (including the gating system) in a flask surrounded by unbounded sand and vibrated to achieve maximum sand compaction around the pattern assembly. Secondly, pouring the molten metal on the coated pattern through the

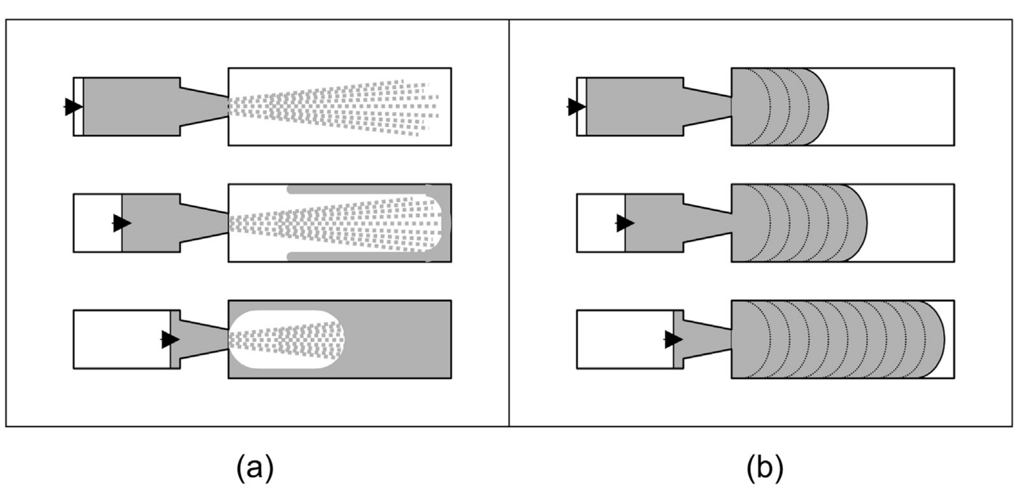


Fig. 12. Schematic illustrating metal flow in (a) conventional die casting; and (b) indirect squeeze casting process [8].

Table 5
Tensile properties of indirect squeeze casting (ISC) AZ91 samples compared to gravity permanent mold cast (GPMC) and high pressure die cast (HPDC) samples of similar thicknesses of ~10 mm [20,23].

Casting process	Temper	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %
ISC	As-cast	112–118	168–185	2.0–3.5
ISC	T4	92–101	228–247	7.0–11.0
ISC	T6	135–140	196–210	2.0–2.5
GPMC	As-cast	82.7	178.4	3.9
HPDC	As-cast	110–130	130–175	0–1

gating system to vaporize the polystyrene pattern leaving a casting which is a replica of the foam pattern. The gases that form during the pattern evaporation permeate through the coating, sand and the flask vents. Some of the unique advantages of the LFC process are close dimensional tolerances, part consolidation, high casting yield, easy casting cleaning, as well as the elimination of mold parting line, sand cores and binders. The LFC process is readily automated and used in production of cast iron and aluminum castings such as engine blocks and cylinder heads.

Major challenges of lost foam casting magnesium compared to iron or aluminum have been its lower heat content in displacing the foam patterns and chemical reactivity with many foam, coating and sand materials. Recent efforts [25] in LFC of magnesium alloys have overcome these challenges by using higher casting temperatures, sand inhibitors (mixture of sulfur and potassium fluoroborate), proper gating, foam types (such as Probead 70) and coatings (Styromol 169.23, Semcoperm M70 or Semcoperm M66L). The application of 40 kPa vacuum was found to enhance filling and produce better quality castings.

6.4. Ablation casting

The filling of aggregate (sand) mold castings can be better controlled (less turbulent compared to high pressure diecasting), but the cooling rate is much lower, thus relatively poor mechanical properties achieved in sand castings. Additionally, in conventional casting processes, the casting contracts away from the mold upon cooling, and the mold expands, opening the so-called ‘air gap’ between the casting and the mold. This air gap controls the rate of cooling, and thus the fineness of the microstructure and the mechanical properties of the casting.

The ablation casting technology [26] removes the aggregate (sand) mold – held together with an environmentally friendly, water-soluble inorganic binder – with water, which is sprayed so as to ablate (i.e., erode by dissolution) away the mold, allowing the water to impinge directly on the casting, see Fig. 13 [26]. The technique achieves an easy removal of both the mold and the more complex internal cores, while providing a high chill rate to the casting. The benefits of ablation appear to extend directly to Mg-based alloys [26]. Perhaps surprisingly, magnesium alloys (AZ91 and AM60) have been found to be docile with respect to ablation, allowing the production of sound Mg alloy prototypes such as an automotive control arm [27].

7. Structural applications

Magnesium is the third most-commonly used structural-metal, following steel and aluminum. With its density about one-fourth of steel and two-thirds of aluminum, magnesium is the lightest structural metal that offers significant opportunities for lightweight applications in automotive, aerospace, power-tools, and 3C (computer, communication and consumer products) industries. For example, magnesium castings are increasingly being used by major automotive companies including GM, Ford, Volkswagen and Toyota [28–36]. Current major automotive magnesium applications include instrument-panel beam, transfer case, steering components, and radiator support. However, the magnesium content in a typical family sedan built in North America is only about 0.3% of the total vehicle weight [28]. This section reviews the historical, current and potential structural use of magnesium with a focus on automotive applications, based on an earlier publication [29].

7.1. Aerospace applications

7.1.1. Historical applications

Historically, magnesium was one of the main aerospace construction metals and was used for German military aircrafts as early as World War I and extensively during World War II [6]. The United States Air Forces’ long-range bombers B-36 and B-52 also contained a large amount of magnesium sheet, castings, forgings and extrusions. The B-36 was reportedly [6] using 12,200 lbs magnesium sheet components; 1500 lbs magnesium forgings; and 660 lbs of magnesium castings in the 1950’s. The 1832 airplanes of Boeing 727 built in 1962–1984 contained 1200 magnesium part numbers including leading & trailing edge flaps, control surfaces, actuators, door frames, wheels, engine gearboxes, power generation components, structural items (not primary), and others [37]. Magnesium was also intensively in the former Soviet aircraft industry: for example, TU-95MS plane had 1550 kg of magnesium, and TU-134 had 780 kg of magnesium components in various locations of airplanes [38]. Unfortunately, many of these applications were reduced in modern aviation due to perceived hazards with magnesium parts in the event of fire and the International Air Transport Association (IATA) legislation limiting magnesium alloys to non-structural parts due to corrosion problems reported in the 1950’s and 1960’s [37].

7.1.2. Current and future applications

Today, despite the remarkable improvement in corrosion resistance of modern “high-purity” magnesium alloys upon the discovery of the effect of iron, copper, and nickel impurities (in ppm amounts) on promoting the corrosion of magnesium [39], the application of magnesium in the commercial aerospace industry is generally restricted to engine and transmission related castings and landing gears. Magnesium is not

(a) Ablation in progress (b) Ablation complete

Fig. 13. Ablation casting process for aluminum and magnesium casting [26].

used in structural applications by major aircraft manufacturers such as Airbus, Boeing and Embraer [38], but found many applications in the helicopter industry such as cast gearboxes and some other non-structural components. Some of the notable aerospace applications include [37]:

- Sikorsky UH60 Family (Blackhawk) main transmission in ZE41 alloy;
- Sikorsky S92 main transmission in WE43A alloy;
- Thrust reverser cascade casting in AZ92A alloy found on Boeing 737, 747, 757 and 767;
- Pratt & Whitney F119 auxiliary casing in WE43 alloy (Fig. 14);
- Pratt & Whitney Canada PW305 turbofan in ZE41 alloy; and
- Rolls Royce tray in ELEKTRON ZRE1 alloy (Fig. 15).

In recent years, there have been renewed interests from the aerospace industry around the world (Europe, North America and China) in resolving the regulatory barriers and technical challenges for magnesium applications. A high-profile European research program, Magnesium for Aerospace Applications (FP6 AEROMAG), has assembled a number of magnesium alloy and component producers to work with the aerospace industry to develop new magnesium alloys and manufacturing processes for aerospace applications. It is expected that, with efforts like this around the world, magnesium will become a major structural material in the future aerospace industry.

7.2. Automotive applications

7.2.1. Historical applications

Magnesium has a long history of automotive use, and the first automotive magnesium application was the racing engine pistons for "Indy 500" in 1921 developed by Dow Chemical [6] in the United States. In 1925, magnesium pistons were first used in Germany, die cast by Elektron Metall Bad Cannstatt (Mahle) and there were more than 4 million of them in operation by 1937 [40]. Another early application of magnesium as an automotive material was a sand cast crankcase on the 1931 Chevrolair by GM [41]. Commercial applications of magnesium sand castings were also reported in England including lower crankcases for city buses and transmission housings for tractors in 1930's [42]. Crankcases and housings were also produced in Germany by high pressure die casting process [43]. Magnesium usage grew throughout the 1930's and then grew exponentially during World War II. With the introduction of the Volkswagen Beetle, automotive magnesium consumption again accelerated and reached a peak in

Fig. 14. Pratt & Whitney F119 auxiliary casing in ELEKTRON WE43 alloy [37].

Fig. 15. Rolls Royce tray in ELEKTRON ZRE1 alloy [37].

1971, the major applications being the air-cooled engine and gearbox castings, which together weighted about 20 kg [44].

However, several factors emerged and combined to cause the reduction and eventual elimination of magnesium as a structural powertrain material after the 1970's [45]. These factors included greater power requirements for the engine which increased both its operating temperature and load, which ultimately resulted in the conversion of the engine from air cooling to water cooling as the AZ81 alloy, and later the AS41 or the AS21 alloys, could not keep up with the required operating environment [45]. The use of water cooling put magnesium at a disadvantage compared with other engine materials because of its poor corrosion resistance. By the time more corrosion-resistant "high purity" alloys AZ91D and AM60B, which replaced AZ91C and AM60A, respectively, were developed in the 1980's, the cost of magnesium alloys had begun to increase, and the use of magnesium castings in automotive applications decreased dramatically although a few applications remained.

Table 6
Global magnesium applications in automobiles.

System	Component	North America	Europe	Asia
Interior	Instrument panel	Yes	Yes	Yes
	Knee bolster retainer	Yes		
	Seat frame	Yes	Yes	Yes
	Seat riser	Yes	Yes	Yes
	Seat pan	Yes	Yes	
	Console bracket	Yes		
	Airbag housing	Yes		
	Center console cover	Yes	Yes	
	Steering wheel	Yes	Yes	Yes
	Keylock housing	Yes		
	Steering column parts	Yes	Yes	Yes
	Radio housing	Yes	Yes	
	Glove box door	Yes		
	Window motor housing	Yes	Yes	
Body	Door inner panel		Yes	
	Liftgate inner panel	Yes	Yes	
	Roof frame	Yes	Yes	
	Sunroof panel	Yes	Yes	
	Mirror bracket	Yes	Yes	
	Fuel filler lid	Yes	Yes	
	Door handle		Yes	Yes
	Spare tire carrier	Yes		
Chassis	Wheel (racing)	Yes	Yes	Yes
	ABS mounting bracket	Yes		
	Brake pedal bracket	Yes		Yes
	Brake/accelerator bracket	Yes		
	Brake/clutch bracket	Yes		
	Brake pedal arm	Yes		
Powertrain	Engine block		Yes	
	Valve cover/cam cover	Yes	Yes	Yes
	4WD transfer case	Yes		
	Transmission case		Yes	Yes
	Clutch housing & piston	Yes		
	Intake manifold	Yes	Yes	
	Engine oil pan		Yes	Yes
	Alternator/AC bracket	Yes		
	Transmission stator	Yes		
	Oil filter adapter	Yes		Yes
	Electric motor housing	Yes		

7.2.2. *Current and future applications*

Vehicle lightweighting is among the available strategies to improve the fuel economy of vehicles of conventional gasoline internal combustion engines or alternative energy powertrains. Magnesium, the lightest structural metal, has emerged as a promising material for lightweighting and become a focus of research and development in many countries around the world. Table 6 is a summary of the current major magnesium applications in automotive industry to the best of the author's knowledge. It shows that magnesium has made significant gains in world-wide interior applications, replacing mostly steel stampings in instrumental panels, steering wheels and steering column components. In the powertrain area, North America is leading the applications of magnesium 4WD (four-wheel-drive) transfer cases in high-volume truck production; while Europe is aggressively expanding the use of magnesium in engine blocks and transmission cases using recently developed creep-resistant magnesium alloys. Only a limited number of body and chassis components are currently made of magnesium, which presents a great opportunity for magnesium to expand its applications in lightweight vehicle construction. This section discusses the current and potential magnesium applications in the vehicle subsystems.

7.2.2.1. Interior. Since corrosion is of less concern in interior, this area has seen the most magnesium applications, with the biggest growth in the instrument panels (IP) and steering structures. The first magnesium IP beam was die cast by GM in 1961 with a mass saving of 4 kg over the same part cast in zinc. The design and die casting of magnesium IP beams have advanced dramatically in the last decade. For example, the current IPs normally have a thickness of 2—2.5 mm (compared with 4—5 mm for the earlier IP beam applications) with more part consolidation and mass savings. Fig. 6(b) shows a magnesium die cast instrument panel beam (6.9 kg) in current GM production of Buick LaCrosse. However, the use of cast magnesium IP beams is recently facing strong competition. IP beams made of aluminum extrusions are used by Mercedes in Europe. IP designs using bent steel tubes (with or without hydroforming) are slightly heavier than magnesium die casting, but significantly less expensive. To maintain and grow its use in IP production, magnesium design and thin-wall casting technology must continue to improve to further reducing weight and cost. Tubular designs using magnesium extrusions and sheet components should also be explored.

The use of magnesium seat structures began in Germany in 1990's, where Mercedes used magnesium die castings in its integrated seat structure with a three-point safety belt in the SL Roadster [46]. This seat structure consisted of 5 parts (two parts for the seat back frame and three parts for the cushion frame) with a total weight of 8.5 kg and varying wall thickness of 2–20 mm [46]. In the material selection for the seat program, magnesium was chosen over plastic, steel sheet and aluminum gravity casting designs. Magnesium die castings made of the high-ductility alloys of AM50 and AM20 offered the best combination of high strength, extreme rigidity, low weight and cost [46]. Similar to the IP development, magnesium seat design and manufacturing have gone through significant improvements in recent years. The latest example is the two-piece (backrest and cushion) design used in the Alfa Romeo 156. The die castings used today for seating structures are as thin as 2 mm, providing even greater weight savings. In North America, Chrysler recently introduced the "Stow-n-Go" seating and storage system for its minivans, where the folding mechanisms require lightweight for easy operation, thus some aluminum is used in the second-row seats and the back frame of the third-row folding seats is magnesium casting [47]. While other materials such as advanced high strength steels (AHSS) and aluminum are also being used for these applications, it is expected that magnesium will make significant inroads into seat components as a lightweight and cost-effective solution.

7.2.2.2. Body. The use of magnesium in automotive body applications is limited but recently expanding. GM has been using a one-piece die cast roof frame since the C-5 Corvette introduction in 1997. Magnesium is also used in the Cadillac XLR roadster's retractable hard-top convertible roof and the roof top frame. The Ford F-150 trucks and SUVs have coated magnesium castings for their radiator support [34], and Dodge Viper has a one-piece magnesium front-of-dash die casting [48]. In Europe, Volkswagen and Mercedes have pioneered the use of thin-wall magnesium die castings in body panel applications. The one-piece die cast door inner for Mercedes S-Class Coupe is only 4.56 kg [48]. The 2010 Lincoln MKT magnesium liftgate inner panel is the first die-cast magnesium closure ever to satisfy 55 mph rear crash requirements [49]. As shown in Fig. 16, the 8-kg inner casting is perhaps the world's largest magnesium casting in size (1379 × 1316 mm) [49]. The key to manufacturing these thin-wall castings (approximately 2 mm) lies in casting design using proper radii and ribs for smooth die filling and to stiffen the parts. These thin-wall die castings, such as closure inners, can often offset the material cost penalty of magnesium over steel sheet metal construction due to part consolidation.

7.2.2.3. Chassis. Cast or forged magnesium wheels have been used in many high-priced race cars or high-performance roadsters. Fig. 17 shows a LPDC magnesium alloy wheel for GM's Corvette. However, the relatively high cost and potential corrosion problems of magnesium wheels prevent their use in high-volume vehicle production. The first-in-industry one-piece HPDC magnesium cradle for the Chevrolet Corvette Z06 weighs only 10.5 kg, and demonstrates a 35% mass savings over the aluminum cradle it replaced [50]. This cradle uses a new AE44 (Mg-4Al-4RE) alloy which offers high strength and ductility at room- and elevated temperatures.

The production of lightweight and low-cost magnesium chassis components such as wheels, engine cradles and control arms depends on the improvement of magnesium casting processes. Various casting processes have been developed for the production of aluminum wheels and chassis parts. These processes include permanent mold casting, low-pressure casting, squeeze casting and semi-solid metal (SSM) casting. The successful adaptation of these processes to magnesium

Fig. 16. HPDC magnesium casting Lincoln MKT liftgate inner (photo courtesy of Meridian Lightweight Technologies) [49].

Fig. 17. LPDC magnesium alloy wheel for Chevrolet Corvette.

alloys will make magnesium castings more competitive to aluminum in the chassis area. For example, recent developments in low pressure die casting and squeeze casting will make lightweight cast magnesium wheels, control arms and knuckles more cost-effective in competing with forged aluminum components. The development of low-cost, corrosion-resistant coatings and new magnesium alloys with improved fatigue and impact strength will also accelerate the further penetration of magnesium in chassis applications.

Hollow structures of aluminum castings and extrusions are presently used in high-volume cradle production such as the welded structures for GM's mid-size cars and the hydroformed tubular subframe for BMW 5 and 7 series. Hollow designs are generally more mass-efficient than solid castings. Cradles and subframes using magnesium tubes and hollow castings would offer more mass savings. The development of hollow magnesium casting processes are needed for these lightweight and efficient chassis applications.

7.2.2.4. Powertrain. The majority of powertrain castings (such as engine block, cylinder head, transmission case and oil pan) are presently made of aluminum alloys, which represents the most significant opportunity for lightweighting with magnesium due to the excellent castability of magnesium alloys. At present, millions of pickup trucks and sport utility vehicles (SUVs) produced in North America have magnesium transfer cases. VW and Audi have high-volume production of manual transmission cases of magnesium in Europe and China. Magnesium valve covers are used by many vehicles in North America, Europe and Asia. The operating temperatures for these applications are below 120 °C, and AZ91 is the alloy of choice due to its excellent combination of mechanical properties, corrosion resistance and castability.

Higher-temperature applications such as automatic transmissions and engine blocks require creep-resistant magnesium alloys. The Mercedes 7-speed automatic transmission case uses AS31 alloy with marginally better creep resistance than AZ91 alloy [51]. Honda introduced a new alloy referred as ACM522 (Mg-5%Al-2%Ca-2%RE) in the production of Honda Insight (a low-volume hybrid gas/electric car) oil pans, achieved a 35% weight saving over the aluminum design [52]. Another significant development is the BMW Mg/Al composite engine block, Fig. 18 [35]. The composite block consisted of an aluminum insert (about 2/3 of the total block weight) surrounded by magnesium alloy AJ62 (Mg-6%Al-2%Sr) (1/3 of the total weight) in the upper section of the cylinder liners and water-cooling jacket. The hypereutectic aluminum alloy insert avoided the use of additional liner technology and facilitated the highly loaded bolt joints for both cylinder head and crankshaft bearings. The insert also included the water jacket, avoiding the potential problem of coolant corrosion with magnesium [35]. The magnesium housing surrounding the aluminum insert, in turn, primarily served the oil ducts and the connection of ancillary units. The gearbox cover and the mounts for both the alternator and vacuum pump were integrated in the housing. The lower section of the crankcase, in turn, also made of die cast magnesium AJ62 alloy, comprised cast-in sintered steel inserts for the crankshaft mounts. This composite design was reported to be 10 kg lighter than the aluminum block, and was in BMW production in the 2000's.

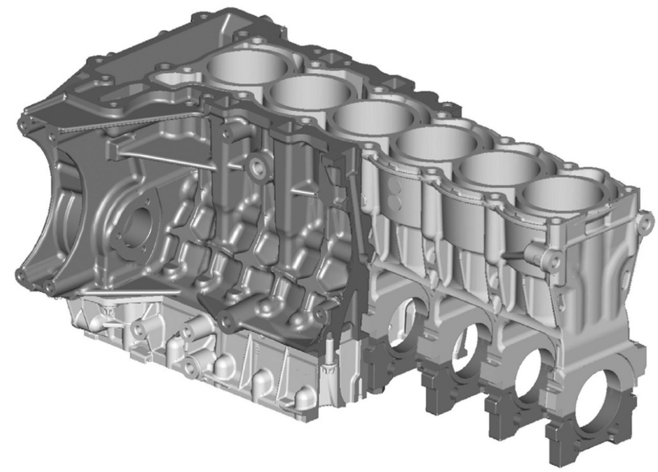


Fig. 18. The BMW composite engine block showing a cutaway of the magnesium exterior revealing the aluminum interior [35].

In the United States, much of the development is jointly sponsored by the US Department of Energy (DOE) and the US Automotive Materials Partnership (USAMP), and led by the three OEMs (GM, Ford and Chrysler). The USAMP Magnesium Powertrain Cast Components (MPCC) Project had the objective of demonstrating the readiness of magnesium alloys for completely replacing the major aluminum components of a V block engine [53]. The MPCC cylinder block achieved a mass reduction of 25% (29% for all of the cast aluminum components were replaced by magnesium). A prototype engine made with a LPDC cylinder block, a Thixomolded rear-seal carrier, and HPDC oil pan and front cover, with all other parts carried over from the baseline aluminum engine, has been completed [54], see Fig. 19. Significant learning has been generated in the dynamometer test of the prototype Mg-intensive engine, promising more magnesium powertrain applications in the future.

7.3. Other applications

The lightweight of magnesium alloys has attracted many other applications beyond the transportation (automotive and aerospace) industries, most notably the electronics and power tools. In addition to its low density, magnesium offers 100 times better heat dissipation than plastics, the best vibration dampening of any metal, ease of machining, electromagnetic shielding, and the major environmental advantage of being recyclable [55].

7.3.1. Applications in electronics

Driven by environmental programs across the consumer electronics industry, portable electronics product manufacturers are opting for light, yet tough magnesium for everything from flash audio/video players to digital cameras, mobile phones, computer notebooks, radar detectors, and more [55].

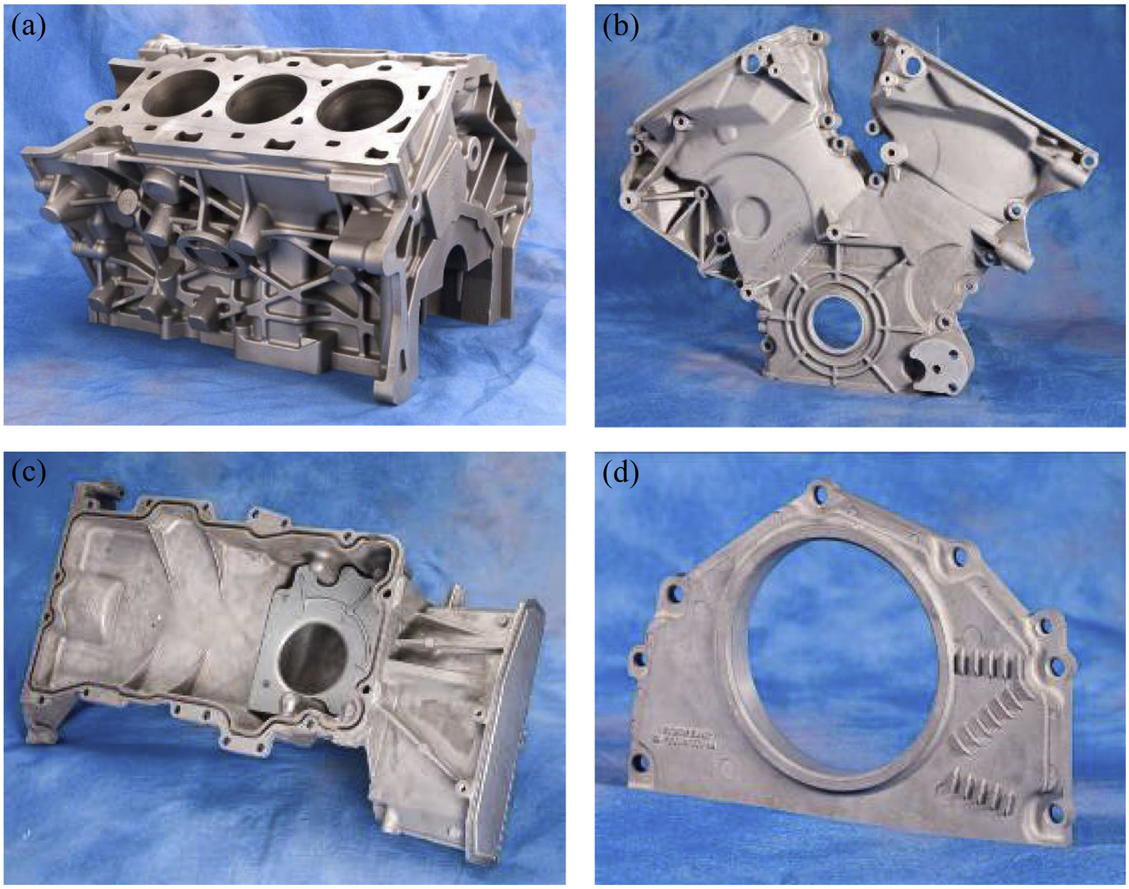


Fig. 19. Magnesium powertrain components from the USCAR magnesium powertrain cast components project; (a) LPDC cylinder block, (b) Thixomolded front engine cover, (c) HPDC oil pan and (d) HPDC rear seal carrier [54].

Magnesium castings meet the design challenges that are instrumental to consumer electronics becoming lighter, thinner, and more mobile. Components that house and protect highly sensitive technology inside these entertainment and communication devices must exhibit strength and durability to withstand daily abuse from being dropped, stepped on, bumped, banged around in transit, and survive even the ultimate test – teenagers.

7.3.2. Applications in power tools

The power tool industry increasingly relies on die-cast magnesium components to offer durable, lighter weight designs that are easier to handle and manage over long work shifts – an important feature, especially for framing and construction crews on the job site [56]. For example, replacing by cast magnesium housings of a 7-1/4-inch Worm Drive power SKILSAW® SHD77M hand-held saws and power nailers shaves a full two pounds off the unit's weight, resulting in less user fatigue issues during work shifts [56].

8. Future outlook

While magnesium is the lightest structural metal and the third most commonly used metallic material in automobiles following steel and aluminum, many challenges remain in various aspects of alloy development and manufacturing processes to exploit its high strength-to-mass ratio for widespread lightweight applications in the transportation and other industries.

8.1. Material challenges

Compared with the numerous aluminum alloys and steel grades, there are only a limited number of low-cost cast magnesium alloys available for structural applications. The conventional Mg–Al based alloys offer moderate mechanical properties due to limited age-hardening response of this alloy system. Since the development of vacuum die casting and other high-integrity casting processes, magnesium castings can be heat-treated with no blisters. Alloy systems with significant precipitation hardening such as Mg–Sn [57,58] and Mg–RE [59] should be developed with improved mechanical properties. New alloys with improved ductility, fatigue strength, creep resistance and corrosion resistance should also be explored. Computational thermodynamics and kinetics [60] will be used to design and optimize these new alloys.

The properties of magnesium alloys can be significantly enhanced if micro- and nano-particles are introduced to form metal matrix composites (MMC). Micro- and nano-sized particles offer strengthening mechanisms in different length scales and provide a tremendous opportunity for a new class of engineering materials with tailored properties and functionalities for automotive applications.

8.2. Process challenges

Although the success of magnesium is primarily attributed to its superior die-castability compared with aluminum alloys, these castings cannot generally be heat-treated due to the porosity intrinsic to die casting that is present. Several recent developments show promise including super vacuum die casting and squeeze casting that drive porosity to minimal levels to enable their heat treatment without blistering. Combined with advanced low-cost alloys, these processes could provide competitive advantages for increased use of magnesium die castings. Other casting processes such as gravity, permanent mold, low pressure and ablation casting, have also been adapted for magnesium although casting rules developed for aluminum need to be modified to compensate for the larger shrinkage with magnesium. These processes are still, nevertheless, important for magnesium due to the need for large hollow castings for structural subsystems like engine cradles that provide the highest mass efficiency. Melt handling, molten metal transfer with minimal turbulence, grain-refinement, die coating as well as casting parameters need to be developed specifically for magnesium alloys to fully utilize their intrinsic properties in these casting processes.

8.3. Performance challenges

There are several performance-related challenges that need significant research efforts. Some of them are highlighted in the current Canada–China–USA "Magnesium Front End Research & Development" project [61].

8.3.1. Crashworthiness

Magnesium castings have been used in many automotive components such as the instrument panel beams and radiator support structures. High-ductility AM50 or AM60 alloys are used in these applications and performed well in crash simulation and tests; and many vehicles, with these magnesium components, achieved five-star crash rating. However, there is limited material performance data available for component design and crash simulation. A recent study shows that magnesium alloys can absorb significantly more energy than either aluminum or steel on an equivalent mass basis [62]. While steel and aluminum tubes fail by progressive folding in crash loading (more desirable situation), magnesium alloys box structures tend to fail by sharding or segment fracture [62,63]. However, the precise fracture mechanisms for magnesium under crash loading are still not clear, and material models for magnesium fracture are needed for crash simulation involving magnesium components. Additionally, new magnesium alloys need to be developed to have progressive folding deformation in crash loading.

8.3.2. Noise, vibration and harshness (NVH)

It is well known that magnesium has high damping capability, but this can be translated into better NHV performance only for mid-range sound frequency; 100–1000 Hz. The low-frequency (<100 Hz) structure-borne noise can be controlled by the component stiffness between the source and receiver of the sound. The lower modulus of magnesium, compared with steel, is often compensated by thicker gages and/or ribbing designs. For high-frequency (>1000 Hz) airborne noise, a lightweight panel, regardless of material, would transmit significantly more road and engine noise into the occupant compartment unless the acoustic frequencies could be broken up and damped [64]. Magnesium, with its low density, is disadvantaged for this type of applications unless new materials with laminated structures are developed for sound isolation.

8.3.3. Fatigue and durability

Fatigue and durability are critical in magnesium structural applications and there is limited data in the literature [65,66]. The effect of alloy chemistry, processing and microstructure on the fatigue characteristics of magnesium alloys need to be studied. Extrusion and sheet products need to be characterized sufficiently to establish links between microstructural features and fatigue behavior. Multi-scale simulation tools can be used to predict the fatigue life of magnesium components and subsystems, which can be validated for automotive applications.

8.3.4. Corrosion and surface finishing

Pure magnesium has the highest standard reduction potential of the structural automotive metals [41]. As noted earlier, while pure magnesium (at least with very low levels of iron, nickel, and copper) has atmospheric corrosion rates that are similar to that of aluminum, magnesium's high reduction potential makes it very susceptible to galvanic corrosion when it is in electrical contact with other metals below it in the reduction potential table. The impact of this susceptibility to galvanic corrosion on the application of magnesium in exposed environments is severe in both the macro-environment and the micro-environment. In the macro-environment, magnesium alloys must be electrically isolated from other metals to prevent the creation of galvanic couples; e.g., steel bolts cannot be in direct contact with magnesium. Isolation can be achieved by replacing the bolt with a less reactive metal, as has been done in the Mercedes automotive transmission case where steel bolts have been replaced with aluminum bolts [46]. Isolation can also be achieved by coating the "other" metal. Finally, isolation can be achieved by the use of shims or spacers of compatible materials of sufficient geometry and size to prevent electrical contact in the presence of salt water, as shown, for example, for the Corvette cradle, Fig. 20 [50]. While the component cost can be competitive with aluminum, the isolation strategies required can often make the application more expensive and thus restrictive in its use.

A major challenge in magnesium automotive applications is to establish the surface finishing and corrosion protection processes. The challenge is two-fold since surface treatments for magnesium play roles in both manufacturing processes (e.g., adhesive bonding) as well as the product life cycle that

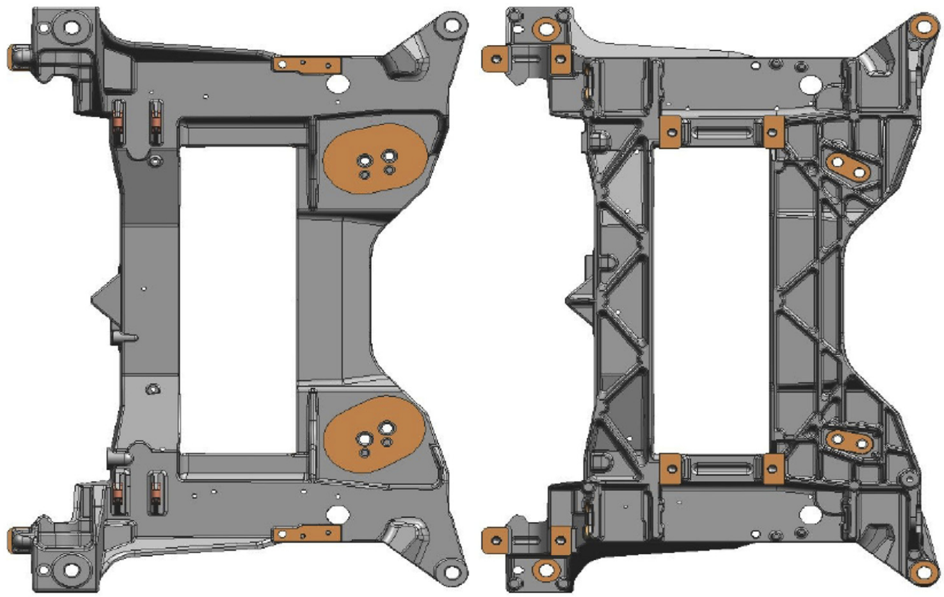


Fig. 20. Aluminum isolator locations for Chevrolet Corvette Z06 magnesium cradle (bottom & top views) [50].

demands corrosion resistance. Furthermore, the current manufacturing paradigm for steel-intensive body structures employs chemistries in the paint shop that are corrosive to magnesium and are additionally aggravated by galvanic couples primarily steel fasteners. Future research will explore novel coating and surface treatment technologies including pretreatments such as micro-arc oxidation, non-chromated conversion coatings, and "cold" metal spraying of aluminum onto magnesium surfaces.

8.3.5. Future developments

The future success of magnesium as a major structural material will depend on how these technical challenges are addressed. These challenges are huge and global, and would require significant collaboration among industries, governments and academia from many counties. One current effort is the Canada–China–USA "Magnesium Front End Research & Development" project funded by the three governments [61]. This project has brought together a unique team of international scope, from the United States, China and Canada, and has developed some key enabling technologies and knowledge base for automotive magnesium applications. The technologies and knowledge base developed in this project not only benefit the automotive magnesium applications using front end structure as a test bed, they also promote primary magnesium production, component manufacturing, fundamental research to advanced computational tools like Integrated Computational Materials Engineering (ICME). Such technologies have been demonstrated in a "demo" structure designed and built by the USAMP team [67], employing friction-stir linear lap welding (FSLW)

(a) (b)

Fig. 21. USCAR demo structure build using (a) FSLW (friction stir linear welding); and (b) LSPR (laser-assisted self-pierce rivet) joining processes [67].

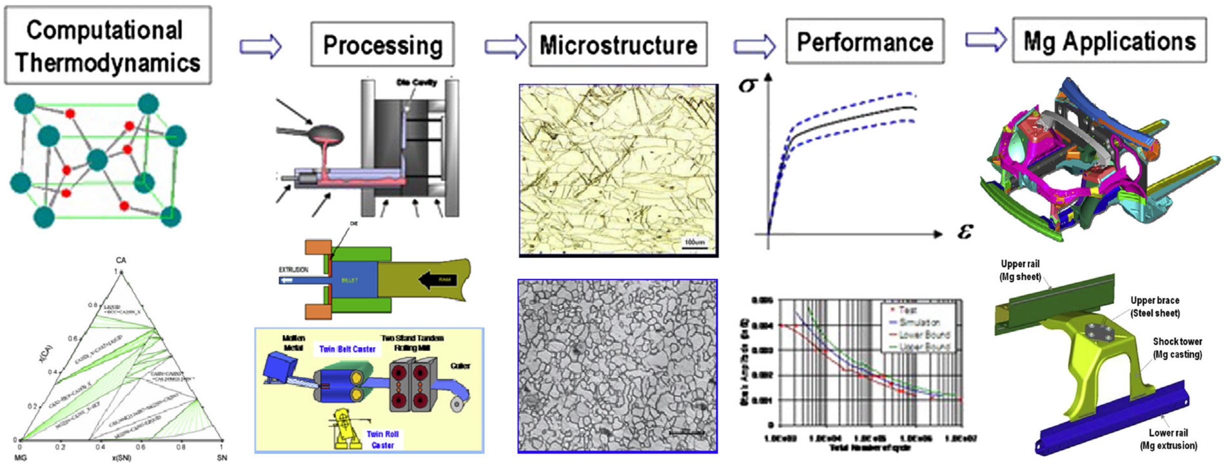


Fig. 22. Integrated Computational Materials Engineering (ICME) framework for magnesium applications.

and laser-assisted self-pierce rivets (LSPR), both with and without adhesive bonding, see Fig. 21. It is very encouraging that many of these international and interdisciplinary collaborations are being nurtured for magnesium applications in many industries.

ICME is the integration of materials information, captured in computational tools, with engineering product performance analysis and manufacturing-process simulation [68]. Currently, the USAMP team is establishing an ICME framework for magnesium applications [69], in collaboration with many institutions around the globe. As shown in Fig. 22, the team is developing and integrating computational models from thermodynamics and kinetics to engineering performance prediction via quantitative processing–structure–properties relationships of various magnesium alloys.

9. Concluding remarks

The compelling need for lightweight, energy-efficient, environmentally benign engineering systems is driving the development of a wide range of structural and functional materials for energy generation, energy storage, propulsion, and transportation. These challenges motivate wider spread use of magnesium - the eighth most common element in the earth's crust and also extractable from seawater [70]. In addition, the ease of recycling, compared with polymers, makes magnesium alloys environmentally attractive. With nearly 100 years of technology development, the magnesium casting industry is well positioned to meet the increasing demands for lightweight structural systems (most notably, automotive systems) in the next few decades.

Will magnesium alloys be considered with equal confidence in comparison with polymers and other metallic systems as solutions for energy and lightweight-materials challenges? The answer is likely "yes", particularly if the rapidly evolving fundamental understanding of the properties of this unique class of materials is captured in models that can be integrated and used for the design of new materials and for prediction of their performance [70]. It is expected that future developments exploiting the new computational and characterization tools available will provide the much needed breakthroughs to design new magnesium alloys and engineering products to increase the use of magnesium, the lightest structural metal!

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