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Towards magnesium alloys for high-volume automotive applications

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ABSTRACT

Reducing vehicle weight is an important approach for increasing fuel economy, addressing regulatory requirements, and meeting consumer needs. Magnesium alloys are among the lightest structural metals and offer tremendous weight saving potential; however, many technical and commercial barriers limit their use in today's cars and trucks. Following a brief review of historical trends in vehicle weight and automotive magnesium, we describe key barriers to wider adoption of magnesium in high-volume vehicle applications. A discussion of manufacturing and processing, in-service performance, and cost requirements identifies specific development needs and opportunities while framing promising paths forward.

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1. Introduction

The automotive industry is incorporating many new technologies into modern cars and trucks as vehicle manufacturers respond to changing consumer preferences and regulatory requirements. Lightweighting offers up to a 7% improvement in fuel economy for each 10% reduction in vehicle weight when combined with an appropriately sized powertrain [1]. Reducing mass also improves vehicle performance attributes such as acceleration, braking, and handling. Between 1995 and 2010, the average weight of a passenger car increased by about 260 lb (118 kg), without a significant change to interior volume [2]. Since 2010, car weight has remained mostly constant. The stability in vehicle weight and recent progress in mass reduction, which comes despite additions of safety, performance, and comfort features, is enabled both by efficient designs and through the use of lightweight materials. Application of advanced high strength steels continues to increase [3] due to an attractive combination of low cost and high strength. Aluminum (Al) alloys, which benefit from low density and relative compatibility with existing manufacturing infrastructure, are experiencing tremendous growth in body and closure applications. The body structure and closure panels for the model year (MY) 2015 Ford F150 are made predominantly from Al sheet, while the Cadillac ATS and CT6 demonstrate a "mixed material" execution using high strength steel as well as Al castings, extrusions, and sheet metal. Carbon fiber reinforced polymer composites are finding application in lower volume vehicles such as the BMW i3 and Corvette Stingray as development efforts deliver lower cost and new manufacturing technologies. However, despite significant weight saving potential, magnesium (Mg) alloys remain minimally utilized. Magnesium alloys make up less than 0.5% of the weight of an average vehicle [3] due to challenges associated with manufacturing and processing, assembly, in-service performance, and cost. In this article, we describe some of the key technology barriers, commercial challenges, and performance targets for automotive Mg alloys. Further, following a discussion of the state of the art in automotive Mg, we detail promising paths forward for development and implementation of this important lightweight material. Our report emphasizes automotive applications, and the reader is encouraged to explore other recent reviews of sheet alloys [4], castings [5], and conversion coatings for corrosion protection [6] for additional details.

2. Applications & design

Magnesium has been used in a wide variety of automobile applications including body, chassis, and interior components. Some examples of Mg applications include instrument panels, steering wheels, engine cradles, seats, transfer cases, and many different housings. These applications were largely developed to provide lower mass components while leveraging magnesium's ability to integrate components into single-piece, thin-wall castings. However, many of the applications have not been sustainable due to the component price, issues related to increasing powertrain temperature, under-hood packaging constraints and, more importantly, the continued development of competitive lightweight solutions that offer a better value proposition, although in many cases, at less absolute mass savings. There are three excellent examples which illustrate the challenges facing the growth of Mg in automobiles: the engine cradle, instrument panel (or cross car beam), and decklid (or trunk) inner panel. A description of each application illustrates some of the challenges to future implementation.

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A Mg engine cradle was used on the Chevrolet Corvette Z06 from model year 2006 through 2013. The Z06 also featured an aluminum hydroformed structure as a variant to the steel structure of the base Corvette during that same time. The magnesium cradle was chosen because it enabled lightweighting in the front of the vehicle and leveraged part integration and design freedom realized by die casting. The key material competition for the Mg cradle was Al. The cradle itself provided lightweighting at a realistic cost compared to the Al solution. However, the cradle needed to be attached to the rest of the body structure, and to prevent galvanic corrosion, a significant isolation strategy was employed. As a result, the cost of corrosion mitigation for the Mg cradle was high enough that it made the aluminum design more favorable.

When the 2014 Corvette Stingray was designed and built, it used an aluminum body structure for all variants, leveraging results from the previous Z06 model. However, unlike the Z06, an Al cradle was selected over a Mg option due to the experience with the previous model, the limited mass savings, and the increased cost. An additional general challenge with a magnesium cradle is its lower stiffness compared to aluminum and steel. The engine compartment is “prime real estate” in the vehicle, and a larger section size is required for magnesium to achieve the same stiffness. This challenge also faces aluminum cradles compared to steel cradles in mainstream vehicles due to the rigorous packaging requirements under the hood.

The case of the Mg instrument panel was described previously by Taub et al. [7]. Instrument Panels (IP) or cross car beams were traditionally made from steel stampings prior to the 2000's. These were complex assemblies of stamped steel components that were welded together. Die cast Mg IP structures were introduced in the early 2000's to reduce mass and leverage the ability to integrate many of the stamped pieces into a single die cast part. These applications were attractive from a performance perspective since they were not exposed to the elements making addressing corrosion much easier. They also improved dimensional stability because of the single piece design. At General Motors, there were numerous examples of high volume Mg IP structures with a peak in usage in 2005 and 2006. However, since that time, the use of Mg for IP structures has continually decreased. One factor in the decline is the rising cost of the parts resulting from both unstable raw material cost and a small supply base for die casting which struggled during the economic downturn in the late 2000's. More importantly, competing engineering solutions provided significant challenges to the Mg die cast solution. A tubular steel design was developed which saved mass compared to previous steel versions. This led to a reduction in the absolute weight savings between the Mg solution and the steel alternatives, resulting in a higher effective cost per kg of weight saved for the Mg options. As a result, other mass reduction opportunities in the vehicle became more attractive. This constant evolution of efficient vehicle design and improvement in the performance of the “baseline” materials like high strength steel is a challenge to many lightweight materials, not just Mg.

A final example of the challenges facing Mg can be illustrated with the Mg sheet decklid which was launched in 2012 on the Cadillac SLS to gain field data on Mg closure performance. This application was a unique opportunity as the Cadillac STS had an all Al decklid made with GM's quick plastic forming (QPF) technology [8], where hot blow forming is used to make high volume automotive components. Using the same tooling, the process was modified to make a Mg version of the decklid inner that could be assembled with an Al outer panel [9, 10]. This was an excellent opportunity to put a Mg sheet component into production and gain tremendous learning. However, it has not become a sustainable application due to the high cost of the component. The cost is driven by many of the key technical challenges associated with Mg. First, the cost of the Mg sheet is higher than Al or steel sheet. While there has been progress with continuous casting, Mg sheet is not available as a commodity. Second, Mg sheet cannot be conventionally stamped into the desired shape. In the case of the decklid, a high-cycle-time, premium forming technology which required the application ***and*** subsequent removal of an expensive lubricant was required. Third, post processing the Mg sheet is more expensive than Al or steel. For example, when the formed Mg decklid was trimmed, a jagged trim edge was present. The edge had to be ground to enable acceptable corrosion performance [11]. Finally, the susceptibility of Mg to general and galvanic corrosion necessitated using a pretreatment to isolate the decklid inner panel from the outer panel and a more complicated hinge attachment strategy with isolators. Each of the four items described above added cost and made the incremental mass savings compared to Al (1.5 kg for the decklid) almost insignificant when considering the increased cost.

Combined, the above examples suggest that improvements in manufacturing & processing, in-service performance, and cost of automotive Mg alloys are needed to promote wider adoption.

3. Manufacturing & processing

The vast majority of Mg components in vehicles are made via die casting, which affords tremendous design flexibility and opportunities for part integration, thereby lowering “system” cost. Following a decline in availability of North American die casting infrastructure over the past decade, recent investments have established new capacity [12,13]. Process technology for die cast Mg is well developed and employed to manufacture components in passenger vehicles, as summarized by Luo [5]. While there is a general need for continued engineering development and implementation in high volume (and clear motivation for higher performance alloys, as discussed below), processing technology challenges are a lower barrier than primary metal cost, mechanical properties, and in-service performance for Mg die castings.

Manufacturing processes for sheet Mg exist which are capable of producing automotive components, including the Cadillac STS decklid described above. However, these processes typically require elevated temperature forming, which increases manufacturing cost and reduces throughput, especially when compared to conventional stamping processes. There is tremendous need for the development of new primary forming processes (e.g. stamping) as well as secondary processes (e.g. hemming) which are used in subsystem assembly, along with magnesium alloys that are more amenable to these processes.

In general, Mg sheet alloys suffer from low formability at temperatures, strain rates, and process conditions typically found in automotive manufacturing. Formability is a complicated function of material and process characteristics, with two general approaches for improvement. First, modifying alloy chemistry and sheet manufacturing process technologies can affect material properties and improve formability. For example, ZEK100 Mg sheet alloy exhibits an increased forming limit across a wide range of strain states when compared to conventional AZ31 sheet alloy at room [14,15] and elevated temperature [16] due, at least in part, to reduced texture in rare earth bearing alloys [17–20]. Similarly, addition of calcium (Ca) to some Mg sheet alloys increases tensile elongation and formability due to the interactions of twinning, recrystallization, and development of favorable texture [21–23]. The effects of modified chemistry on texture should be leveraged with other alloying effects such as a reduced ratio of non-basal to basal critical resolved shear stresses [24–26], increased propensity for cross slip [27], modification of twinning behavior [28,29], strengthening using novel precipitate chemistries [30], and promotion of non-basal precipitates to preferentially harden basal slip systems [31,32]. Novel sheet manufacturing processes can also deliver improved formability, such as by reducing grain size [33] or controlling texture [34–36]. Continuous casting techniques to directly produce sheet, such as twin roll casting and twin belt casting, may also offer modified microstructures and properties to aid in formability.

In addition to modifying alloys and sheet manufacturing processes, implementation of new part forming processes can improve formability and manufacturability of complex shapes. This could include improvements to elevated temperature aluminum forming processes like

Table 1
Typical mechanical properties of automotive sheet materials and equivalent Mg yield and fatigue strength.

	Density (g/cm^3, typ.)	Elastic modulus (GPa, typ.)	Yield strength (MPa, typ.)	Fatigue strength (MPa, typ.)	Mg equivalent yield strength (MPa)	Mg equivalent fatigue strength (MPa)
Steel (mild)	7.7	210	250	85	78	27
Steel (DP980)	7.7	210	910	310	285	97
Steel (future)	7.7	210	1200	450	376	141
Al sheet (5182-O)	2.7	69	120	40	87	29
Al sheet (6022-T43)	2.7	69	135	45	98	33
Al sheet (future)	2.7	69	470	160	340	116
Carbon fiber composite (low)	1.6	12	150	–	238	–
Carbon fiber composite (high)	1.6	45	475	–	753	–

warm forming or QPF, or new processes that use unconventional strain rates [37–39], localized forming [40], or a myriad other possibilities. However, the development of novel processing approaches must be accompanied by clearly articulated vision for compatibility with automotive manufacturing costs and cycle times. In addition, these processes must eventually be implemented in a common way with capacity around the world to support global vehicle programs. The large search space and complicated interactions between alloy chemistry, deformation mechanisms, microstructure, and processing parameters merits (and perhaps necessitates) a focused, integrated computational materials engineering (ICME) approach to ensure success.

In the long-term, the best Mg sheet technologies will employ an optimized combination of alloying, unique sheet manufacturing processes, and improved component manufacturing technologies. For near-term applications, developing a robust set of alloys compatible with existing or slightly modified automotive manufacturing processes should be prioritized. As a directional target, development of Mg sheet alloys able to achieve room temperature forming limit behavior similar to 6022-T43 Al would be of considerable benefit. Continued manufacturing R&D and basic science connecting process conditions to deformation mechanisms and ductility deserves sustained emphasis as means to optimize alloy-process combinations. Continued development and scale-up of manufacturing processes capable of producing complex shapes without the use of exotic lubricants/coatings or unconventional heating/cooling equipment is also highly desirable. In parallel, further developing and increasing the throughput of thermal processes is required, including developing processes like thermal hydroforming and electrohydraulic forming. Realistic targets for part complexity include door inner panels, having modest surface quality requirements while remaining difficult to form.

While much less prevalent than sheet metal, extrusions are also applied in automotive manufacturing. Magnesium extrusions typically suffer from low extrusion rates which increases part cycle time and cost. However, the unique properties of Mg extrusions [41–43] suggest that further investigation is worthwhile. Interesting variations on extrusion processing yield vastly improved extrusion rates and intriguing properties [44,45]. Similarly, alloy chemistry has a dramatic effect on extrudability [46,47], providing a potential route towards automotive relevance. Commercial automotive Al extrusion achieves rates of approximately 10 to 60 m/min, compared to Mg extrusions which generally fall between 2 and 10 m/min [46–48]. New Mg extrusion processes and alloys should target extrusion rates comparable to Al as a path towards cost competitiveness before dedicating significant effort to improved properties or part complexity. Post-extrusion machining or hole drilling introduces additional challenges. Extrusions are often attractive due to their low die cost, but their component cost increases significantly when substantial machining is performed. The need for safe management of magnesium machining shavings may add to this cost.

4. In-service performance

Mg alloys, like any material, must exhibit certain mechanical performance characteristics for application in automotive components. However, the wide range of structural demands across a vehicle complicates development of specific property targets. While a few components in a vehicle structure are primarily strength- or stiffness-limited, most components contribute to both strength and stiffness in varying degrees. The required mechanical properties and weight reduction potential for Mg alloys therefore vary throughout a vehicle. Nonetheless, in planning for future R&D efforts it is critical to gauge the mechanical behavior of today's alloys and to identify the areas of greatest need. To accomplish this, we calculate the Mg yield strength, fatigue strength, and elongation to failure necessary to produce components with a strength-limited weight reduction potential equal to the stiffness-limited weight reduction potential when compared to steel, Al alloys, and carbon fiber reinforced polymer composites.

The mass ratio of a Mg beam to a steel beam, for example, with equivalent bending stiffness is

$$MR_E = \frac{m_{Mg}}{m_{St}} = \sqrt{\frac{E_{St}}{E_{Mg}}}\frac{\rho_{Mg}}{\rho_{St}} \quad (1)$$

where E_i is elastic modulus, m_i is mass, and ρ_i is density [49]. Elastic modulus and density are approximately constant for alloys and thus the stiffness-limited mass ratio of Mg to steel and Al is constant at 0.49 and 0.80, respectively. Using representative low elastic modulus and high elastic modulus carbon fiber composites (see Table 1) the stiffness-limited mass ratio is 0.56 and 1.09, respectively.

While the stiffness-limited mass ratio is approximately constant for any pair of materials, the strength-limited mass ratio changes with yield strength, which varies across a wide range. For the strength case we assess the bending strength of two different beams and determine the failure strength necessary such that the strength-limited weight reduction potential equals the stiffness-limited weight reduction potential, producing the relationship

$$\sigma^f_{Mg} = \left(\frac{\sigma_{St}^{(2/3)}}{MR_E}\frac{\rho_{Mg}}{\rho_{St}}\right)^{\left(\frac{3}{2}\right)} \quad (2)$$

where σ_f is the failure strength of the material which could be the yield strength, tensile strength, or fatigue strength [49]. Table 1 provides typical mechanical properties for common automotive sheet materials and potential "future" materials, equivalent Mg yield strength, and equivalent Mg fatigue strength calculated using Eq. (2).

We also determine equivalent elongation to failure during plastic deformation by equating the area under a simplified stress strain curve per unit volume. The equivalent Mg energy absorption, U_{Mg}, as compared to Al is simply

$$U_{Mg} = \frac{U_{Al}}{MR_E}\frac{\rho_{Mg}}{\rho_{Al}} \quad (3)$$

Equivalent energy absorption calculated this way is relevant only for cast materials (Mg and Al) where deformation and energy absorption occurs mostly via bulk plastic deformation. In sheet materials,

Table 2
Typical mechanical properties of automotive cast Al alloys and equivalent Mg properties.

	Density (g/cm^3, typ.)	Elastic modulus (GPa, typ.)	Yield strength (MPa, typ.)	Fatigue strength (MPa, typ.)	Elongation to failure (%)	Mg equiv. yield strength (MPa)	Mg equiv. fatigue strength (Mpa)	Mg equiv. elongation to failure (%)
Al casting (T4)	2.7	69	120	60	18	87	43	20
Al casting (T6)	2.7	69	245	110	9	177	80	10
Al casting (future)	2.7	69	300	150	20	217	108	22

comparison of area under the tensile stress strain curve may not accurately reflect energy absorption in service due to strong anisotropy, deformation by bending or buckling, and other factors. Table 2 indicates typical mechanical properties of cast automotive Al alloys and equivalent Mg properties.

This analysis estimates equivalent properties necessary for maximum weight reduction of a beam that is both stiffness- and strength/ductility-limited; further increase in strength or ductility will enable weight reduction of a purely strength- or ductility-limited beam (respectively) but will have less effect on the majority of components that are also stiffness-limited. Our analysis assumes no change to shape factor, which is a function of cross section and size. While tailored geometry increases stiffness and strength for beams of any material, setting shape factor constant compares beams of similar geometry as required by many packaging and manufacturing constraints. We note that not all components behave like beams, geometry changes are likely during introduction of new materials, and the mechanical behavior of complex systems cannot easily be reduced to the tensile stress-strain characteristics of individual materials; as a result, this analysis only provides approximate Mg properties useful for significant weight reduction rather than exact targets. In Tables 3 and 4 we compare these target Mg properties to the properties of today's alloys.

In general, the yield, tensile, and fatigue strength of today's Mg sheet alloys are effectively equivalent to high strength steel (DP980), 6000 series Al, and “low” property carbon fiber/polymer composites. However, significant improvements in Mg sheet strength are needed in order to meet the stiffness-limited mass ratio as compared to next-generation steel, high strength Al alloys, and “high” property carbon fiber/polymer composites; advanced steels already exceed 1500 MPa tensile strength and there are active research programs to produce automotive aluminum with tensile strength exceeding 500 MPa. Similarly, cast Mg alloy strength is sufficient for meeting the stiffness-limited weight reduction potential versus cast Al alloys, however the ductility of today's Mg alloys falls short.

Along with mechanical performance, durability in real-world driving environments poses a critical barrier to wider adoption of Mg alloys; Mg corrosion protection and coatings are essential for implementation in high volume vehicles. As discussed in the application examples above, the cost of corrosion protection and isolation of Mg components can offset the weight savings benefit, even for very efficient designs and processes. Although freestanding Mg alloys often exhibit satisfactory corrosion behavior, implementation in a vehicle requires joints with other materials, creating problematic galvanic couples. As one of the most anodic structural materials, Mg corrodes readily in galvanic contact with automotive materials. Broadly, corrosion protection approaches can be categorized as corrosion resistant alloy designs, coatings, or design/isolation strategies. Although some alloying additions can be used to promote passivation in automotive relevant environments, these include elements such as lithium [66] and arsenic [67,68] which, while worthy of continued investigation, are undesirable from a cost and toxicity perspective. Further, while the objective of “stainless Mg” is meritorious, alloying for corrosion protection is complicated by interaction with alloy strengthening and precipitation hardening as well as recycling. Hence while continued long-term investigation of passive Mg alloys is worthwhile, greater effort should be expended towards coating and isolation development. Corrosion coatings and isolation strategies for Mg include too wide a range of technologies and new concepts to be summarized here. However, no clear winner has emerged from recent engineering studies [69] and there is great need for new concepts and continued development of existing ideas. Corrosion performance comparable to low copper 6xxx series Al sheet alloys, such as 6022-T43, is a reasonable target for Mg alloys and joints between Mg and other materials. New developments must target delivering a suite of engineered coating and isolation solutions while maintaining compatibility with the conventional paint and coating processes used for other materials.

5. Material cost

High cost is a major barrier to the introduction of Mg alloys in high volume vehicles. In the U.S., primary Mg sells at a spot price of about \$2.15 per pound [70] which is approximately double the U.S. spot price of primary Al [71] and significantly more expensive than the various sources of steel. It is also notable that the Al and steel markets enjoy robust secondary metal volume, which further reduces their cost and energy impact. The Mg price penalty by comparison to Al is particularly damaging for die casting applications where primary metal makes up a relatively large portion of final part cost; primary metal makes up a smaller portion of wrought product costs, but is nonetheless important. Further, as shown in Fig. 1, over the past 15 years the market price of primary Mg has varied between \$1.14 and \$3.15 per pound [70] compared to the market price of primary Al, which has only varied from \$0.65 to \$1.25 per pound [71]. Price volatility makes long-term planning, contracting, and purchasing difficult, compounding the commercial barriers to Mg. Part of the variability in Mg price is due to the small size of the market; worldwide production of primary Mg in 2014 was only 907 thousand metric tons [70], less than 2% of primary Al production [71] and only about 0.05% of raw steel production [72]. Price variability in the Mg market is also partly due to the limited number of sources; 88% of worldwide primary Mg is produced in China, which is subject to an antidumping duty in the U.S. [70]. The high price and price variability of Mg reduces demand and presents a commercial and technical conundrum: low demand limits investment in new facilities and technologies, while low investment hinders deployment of

Table 3
Sheet Mg target properties compared to existing alloys. The commercial availability and manufacturing readiness of the reported alloys decreases from left to right, varying from commercial AZ31 sheet to best-in-class laboratory sheet.

	Target range	AZ31 [A,B,C,D,E]	ZEK100 [F,G]	ZEK410 [G]	MgGdYAgZr (NanoSF) [H]
Yield strength (MPa)	100–350	150–220	160–200	185–245	575
Tensile strength (MPa)	175–450	250–290	230–240	275–285	600
Fatigue strength (MPa)	60–135	55–85	NR	NR	NR

NR: not reported.
A [50]; B [51]; C [52]; D [53]; E [54]; F [55]; G [56], H [57].

Table 4
Cast Mg target properties compared to existing alloys with the temper shown in parentheses. The commercial availability and manufacturing readiness of the reported alloys decreases from left to right, varying from commercial AM60B-F to best-in-class laboratory NZ30-T6.

	Target range	AM60B (F) [A,B,C]	AZ91D (F) [A,B,C,D]	AE44 (F) [E,F,G]	NZ30 (T6) [H,I]
Yield strength (MPa)	90–220	115–130	150	100–135	188
Tensile strength (MPa)	165–270	205–225	230	185–240	280
Fatigue strength (MPa)	45–110	50–70	50–70	45	NR
Elongation to failure (%)	10–22	6–8	3	6–12	11

NR: not reported.
A [50]; B [58]; C [59]; D [60]; E [61]; F [62]; G [63]; H [64]; I [65].

new technology, sustaining high prices and price variability. Fundamental R&D and pilot scale demonstration of new primary Mg extraction technologies must continue, coupled with careful consideration of the large increase in scale required for new concepts to achieve commercial viability.

Most of the common alloying additions for Mg such as aluminum (Al), zinc (Zn), zirconium (Zr), and manganese (Mn) are similarly employed for other, higher volume metal alloy systems. Rare earth elements, however, are not as widely used for structural metal alloying due in part to high cost and considerable supply risk. Several commercial Mg alloys use rare earth alloying additions with particular incorporation of rare earth mischmetal (RE) or neodymium (Nd), for example: AE44 (4 wt.% RE), WE43 (2.5 wt.% Nd, 3.3 wt.% RE), and ZEK100 (0.5 wt.% Nd). The addition of rare earth elements to Mg alloys improves creep performance [73,74], mechanical properties across a range of temperatures [75,76], and texture and formability in wrought products [56, 77–80]. Unfortunately, while rare earth bearing Mg alloys are a valuable low volume technology supporting early automotive applications, they are not suitable for use in long-term, high volume production. The U.S. Department of Energy identifies several rare earth elements, including Nd, as "critical materials" that are simultaneously essential for clean energy technologies and also subject to significant supply-chain risk [81]. This combination of characteristics presents a considerable barrier to producing the volume of material required for significant weight reduction across the vehicle fleet. As an example, consider incorporating 500 lb of Mg alloys (about 30% of body and closure weight) into 50% of all new vehicles produced for the North American and European vehicle markets. Using alloys with 0.5 wt.% Nd would require about 13.8 kt of Nd metal, while using alloys with 5 wt.% Nd would require about 1380 kt of Nd metal. In 2015 the worldwide supply of Nd oxide is estimated to be 33 kt with demand for at least 20 kt from other technologies such as magnets [81]. High volume application of Nd bearing Mg alloys would therefore overwhelm the Nd market while competing against other clean energy technologies with greater tolerance to material cost increases. In the next 5 to 10 years, continued development and application of RE bearing Mg alloys should continue as a promising approach for increasing Mg content in vehicles; however, to achieve the long-term vision of significant Mg content across many vehicle platforms, focus on non-RE alloys is essential. Promising work in non-RE systems such as Sn bearing casting alloys and Ca bearing sheet alloys should be emphasized as feasible paths to lower cost Mg components. Care must be taken to ensure that new alloys and the corresponding corrosion solutions are developed with recycling in mind. Closed loop recycling has been critical to enable the growth of aluminum in the automotive industry. Enabling closed loop recycling, with limited introduction of "virgin" metal, and even potentially combining casting, extrusion, and sheet recycle streams could be key to driving down the net cost of using magnesium.

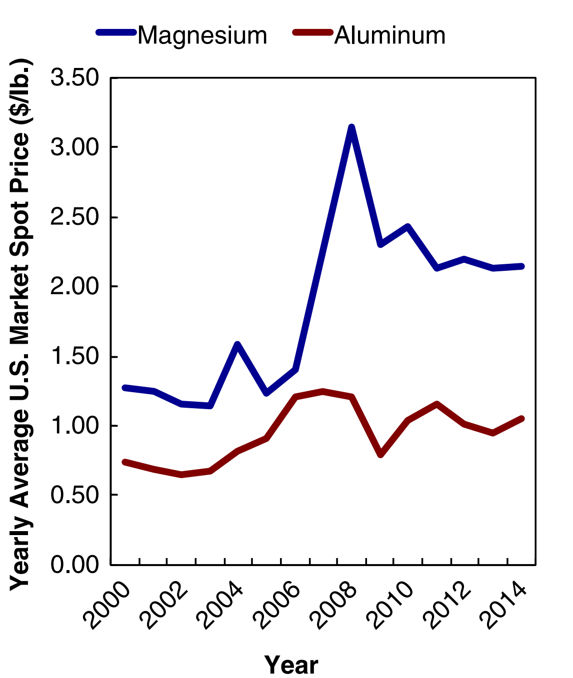

Fig. 1. Average U.S. market spot price for primary Mg and Al. Data from [70,71].

6. Promising paths forward and conclusions

Many technical and commercial challenges must be overcome to achieve the long-term vision of significant Mg applications within a lightweight, multi-material vehicle architecture. While sustained, broad effort is needed, our discussion highlights several of the key requirements for manufacturing & processing, in-service performance, and cost.

In the near term, reduction of primary metal cost and deployment of multiple low-cost, automotive-relevant corrosion protection technologies will have the greatest impact by increasing the competitiveness of Mg die castings as compared to conventional Al die castings. The cost of primary Mg presents a formidable commercial and technical challenge; investigation of new extraction technologies is underway and must continue. However, there is no clear "winner" among Mg extraction processes and the technical community should continue to work towards novel concepts that are commercially and technically feasible. Likewise, the existing corrosion protection approaches do not generally provide an adequate combination of performance and low cost for the wide variety of components and requirements in a vehicle. Sustained effort in developing and deploying advanced, low cost corrosion protection schemes would help unlock many potential applications for automotive Mg.

In the medium term, development of low-cost Mg sheet alloys compatible with slightly modified processing equipment available today, new sheet forming processes capable of delivering at automotive cycle times and costs, and various combinations thereof would create vast new opportunities for Mg. While rare earth bearing alloys are closest to meeting these requirements today, emphasis on non-rare earth bearing sheet alloys must increase. Improving mechanical properties will enable wider application of Mg alloys, however our analysis suggests that today's Mg alloys compare favorably with today's Al alloys, steels, and composites. That Mg alloys find only limited use indicates that high cost, limited processing technology, and compatibility with existing infrastructure are greater barriers than mechanical properties. As the properties of other material systems improve, cast Mg alloys with 110 MPa fatigue strength, 220 MPa yield strength, 270 MPa tensile strength, and 20% elongation to failure will support continued competitiveness. Development of sheet Mg alloys with 135 MPa fatigue strength, 350 MPa yield strength, and 450 MPa tensile strength are similarly attractive and deserving of development effort.

Several other areas also require attention and have not been discussed here. For example, the development of ICME tools and continued exploration of the fundamental science that underpins Mg behavior will create new opportunities for accelerated development and application towards vehicle weight reduction. This approach is critical to developing material cards and process models necessary to virtually represent magnesium's performance in an automobile; as Mg R&D continues, integrating new knowledge into commercial CAE tools while educating and interfacing with the automotive design community is a necessary step towards greater deployment of Mg components. Finally, joining and assembly of Mg structures in an automotive manufacturing environment is sufficiently complex and important to deserve an independent review. Many of the components used in the automobile are limited by the strength or durability of their joining strategy, so the importance of this topic must not be minimized.

There is substantial opportunity for innovation in alloying, processing, and integration of magnesium. New ideas, new risks, and new entrants to the Mg research universe are encouraged. The very low density of Mg underpins its tremendous value; continued emphasis within the technical and commercial communities can drive reduced weight, improved performance, and a strong future for automotive applications of Mg alloys.

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