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Towards magnesium alloys for high-volume automotive applications

William J. Joost [a,*], Paul E. Krajewski [b]

[a] Vehicle Technologies Office, U.S. Department of Energy, Washington, DC 20585, United States
[b] General Motors Global Research and Development, Warren, MI 48090, United States

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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.

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.

* Corresponding author.
E-mail address: william.joost@ee.doe.gov (W.J. Joost).

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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