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Potential Automotive Uses of Wrought Magnesium Alloys[1]

by

L. Gaines, R. Cuenca, F. Stodolsky, and S. Wu[2]
Energy Systems Division
Argonne National Laboratory

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[2]Johnson Matthey Electronics, Spokane, Washington.

DISCLAIMER

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L. Gaines, R. Cuenca, F. Stodolsky,[1] and S. Wu[2]

Argonne National Laboratory, Argonne, IL 60439

Abstract. Vehicle weight reduction is one of the major means available to improve automotive fuel efficiency. High-strength steels, aluminum (Al), and polymers are already being used to reduce weight significantly, but substantial additional reductions could be achieved by greater use of low-density magnesium (Mg) and its alloys. Mg alloys are currently used in relatively small quantities for auto parts, generally limited to die castings (e.g., housings). Argonne National Laboratory's Center for Transportation Research has performed a study for the Lightweight Materials Program within DOE's Office of Transportation Materials to evaluate the suitability of wrought Mg and its alloys to replace steel/aluminum for automotive structural and sheet applications. Mg sheet could be used in body nonstructural and semi-structural applications, while extrusions could be used in such structural applications as spaceframes. This study identifies high cost as the major barrier to greatly increased Mg use in autos. Two technical R&D areas, novel reduction technology and better hot-forming technology, could enable major cost reductions.

INTRODUCTION

We considered novel applications for Mg in passenger cars, beyond the currently-used die castings, including wrought parts (sheet or extrusions) and novel applications of castings. The scope included possible material modifications, as well as process or design improvements to make the substitution technically and economically feasible. We defined the material requirements for parts in each of the main vehicle systems, characterized the properties of Mg and its alloys, and described the production and fabrication processes. We then discussed possible material and design modifications and the relevant factors for substitution. Examples provided by the history of Al substitution were examined, as appropriate. Finally, we identified potential areas for increased automotive use of wrought Mg and remaining barriers to such use, recommending R&D areas to overcome these. A more detailed version of this paper is available (1).

[1] Argonne National Laboratory, 955 L'Enfant Plaza North, SW, Suite 6000, Washington, DC 20024

[2] Current address: Johnson Matthey Electronics, 15128 East Euclid Ave., Spokane, WA 99216

RATIONALE FOR CONSIDERING MAGNESIUM

Magnesium is an attractive material for automotive use, primarily because of its light weight — 36% lighter per unit volume than Al and 78% lighter than iron (Fe). When alloyed, Mg has the highest strength-to-weight ratio of all the structural metals. Since the first oil crisis in the 1970s, there has been an economic and legislated move to make cars lighter in weight to improve fuel efficiency and reduce emissions. Cars have been made lighter by a combination of down-sizing, new designs (such as cab forward and front-wheel drive), and shifts to lighter materials. The most striking material shifts have been from iron to high-strength steel (HSS), and from iron and steel to Al and plastics. But Mg offers even greater potential to reduce weight by displacing steel, and additional incremental savings by displacing Al and plastics from uses already taken over from iron and steel. Current production-model cars contain many small Mg castings, averaging around 6 lb/car, with increased use projected. Some larger parts are in use or being prototyped, such as entire dashboard panels made from a single Mg casting. Few sheet or extruded parts are used, but the potential exists.

Magnesium is abundant. It is the eighth most common element; seawater, the main source of supply, contains 0.13% Mg, which represents a virtually unlimited supply. Magnesium is also recyclable, and instituting a recycling system would extend supplies and save energy. Major increases in automobile usage would eventually require U.S. production capacity expansion.

Several drawbacks (most amenable to technical or institutional fixes) have limited the growth of Mg usage in automobiles. The most important factors are the material's physical properties, some of which are less desirable than its low density. Table 1 compares physical properties of Mg, Al, and iron. Mg is very reactive, but it can be protected with applied coatings or simply allowed to build up a naturally occurring oxide or sulfate coating. Corrosion has also been a concern. However, development of new alloys has helped achieve acceptable properties.

The key factor that inhibits the massive use of Mg is its relatively high and unstable price (the average 1993 price was $1.48/lb, with a low of $0.88). On a per-pound basis, magnesium costs 3.5-6 times as much as steel and 1.7-2.8 times as much as aluminum (2). On a volume basis, the differential is considerably reduced, with Mg's price varying from 10 to 80% above Al's and from 20% below to 30% above steel's. And Mg may have lower fabrication and joining costs, substitution by lightweight materials may enable secondary weight savings, and lifetime fuel costs are reduced, so the total life-cycle cost of a Mg part may actually be lower than that of one made from another material.

TABLE 1. Comparison of Material Properties

Property	Magnesium	Aluminum	Iron
Crystal Structure	hcp	fcc	bcc
Density at 20°C (g/cc)	1.74	2.70	7.86
Coefficient of Thermal Expansion, 20-100°C ($\times 10^6$/°C)	25.2	23.6	11.7
Elastic Modulus (10^6 psi)	6.4	10	30
Melting Point (°C)	650	660	1536

There also has been a concern that the price of Mg may not represent its true production cost, because of the lack of competition in the industry. Even if current prices accurately reflect costs, process R&D could significantly reduce the cost of Mg production. Another factor is tariffs, which raise the cost of imported material, especially from countries that are not most-favored nations, to the U.S. market. Therefore, although Mg is currently more expensive than its competitors, improvement in its relative position is possible.

Another important factor is ease of fabrication and joining. Magnesium is quite easy to form; often, operations that require several steps for steel can be done in only one step for Mg. However, because of its crystal structure, Mg fabrication must be done at elevated temperatures (200-315°C), and thus cannot use the large and very capital-intensive machinery in place for fabricating steel parts. Considerable investment would be required if automakers were to shift to Mg for major body parts. However, especially with possible improvements in hot-forming, operating costs could be lower for Mg parts than for steel parts.

Safety in fabrication and use is an overstated concern. Because Mg is perceived as highly flammable, its safety as an automotive material is questioned. However, because of its high heat conductivity, only small chips and shavings can sustain combustion; parts >3 mm in thickness would cease burning when the heat source was removed. Appropriate safety precautions are required during machining. Another safety issue is the impact resistance of Mg structures; we find that crash safety standards can be maintained.

Since the impetus for lightweighting automobiles is to save gasoline, it is important to make sure that there is a net energy savings over the life cycle of the vehicle. As with Al, Mg production requires large quantities of electricity (typically 5-10 kWh/lb for the reduction step only). It is easy to show that there is indeed a net energy savings by substituting lighter materials in automobiles. Volvo's concept car used several lightweight materials, including about 50 kg (110 lb) of Mg for the wheels, chassis, and engine block, and was estimated to have a lifetime energy consumption (vehicle production plus use) less than 60% that of an equivalent-sized conventional automobile (3). In addition, new, less energy-intensive production processes are being considered, and savings can be further increased by material recycling at the end of the product's life cycle.

POSSIBLE MAGNESIUM USE IN AUTOMOBILES

The majority of auto parts and components are made from a short list of common materials. The simplest approach is to look at material use by major system, and then correlate the material with function and/or manufacturing process. The three major systems or component groups are the **body**, the **powertrain**, and the **chassis**. The major systems and subsystems, each made primarily of only a few types of materials, are shown in Table 2.

The **body** is the single largest group (>40% of total mass). Metals (mostly steel) are the first choice for structural components. Mechanisms are made primarily from metals (with use of some plastic parts increasing), and most lightly-stressed housings

TABLE 2. Components in the Three Major Auto Systems

Body	Powertrain	Chassis
unibody and closures	engine and accessories	suspension steering system
glass	engine electricals	bumper system
hardware	engine controls	brake system
exterior and interior trim	engine cooling system	subframes
body electricals	transmission or transaxle	fuel storage system
seats	clutch (if manual)	chassis electricals
passenger restraints	drive line (rear-wheel drive)	exhaust system
instruments and controls	differential	wheels and tires
climate control	transfer case	

are molded from plastics. The best opportunity for wrought Mg in the body is the use of extrusions on primary structures, such as spaceframes. Even if Mg spaceframes do not become economic in the mass market, penetration in the specialty automotive market (50-100,000 units/year) would significantly increase Mg usage. There could also be opportunities for seat frames, where Mg castings are already being used, and a combination of castings, extrusions, and perhaps sheet could be competitive. The use of Mg sheet in body panels would require development of an economical, high-volume hot-forming process.

The components in the **powertrain** are markedly different from those in the body. The engine and transmission, the main mechanical groupings in the vehicle, are characterized by complex assemblies of many individual components. A great diversity of materials is used. Magnesium castings are replacing some of the iron and even Al castings in some housings and covers. However, Mg does not have the creep resistance of Al, and therefore it is unlikely to be used for the two most massive and critical housings in the engine: the block and the head. But in the transmission, where operating temperatures are much lower, Mg could eventually replace Al in the rather massive main housing. In fact, Mg housings are already used in transfer cases, a similar application. There are probably few opportunities for wrought Mg in powertrain components, where even wrought Al has gained little hold.

The **chassis** components are highly diverse, with characteristics between those of the other groups; the mechanisms are simpler, and many components also have structural functions. The materials are diverse, but iron and steel still play a major role. Components with significant structural function (e.g., the suspension and subframes) are dominated by steel, while those with mainly mechanical functions (e.g., the steering and brake systems) include more diverse materials. Al is gaining share among the chassis housings and other complex castings, and Mg could substitute for many of these, especially in unsprung components, where low mass is key. Wheels were one of the first applications for Mg, and development of a competitive production process based on welded extruded and/or stamped components could enable wide use. Extruded Mg suspension links (especially in the rear) can be used, as shown on the lightweight, experimental Ford "Synthesis." Most opportunities for Mg use in the chassis require castings, but some extrusions could be used.

CONCLUSIONS

Technical problems associated with the manufacture of wrought Mg components can surely be addressed by research. A program to prototype and test a Mg spaceframe or novel hybrid structure, for instance, could become the focus for other, process-related studies (forming, joining, etc.), calling immediate attention to an underutilized material. Such a structure could form the core of a super-lightweight car that could achieve 40% mass reduction. This goal appears optimistic for an Al-intensive vehicle; it may be technically possible with advanced composites, but the economics are currently unattractive. However, the economics of a Mg-intensive body (perhaps including a lightweight plastic skin) might prove more attractive. Other opportunities for prototyping and testing include seat frames made from extrusions, sheet, and castings combined, plus some suspension systems components.

Technical questions remain about high-volume Mg manufacturing, corrosion (galvanic), spot welding, adhesive bonding, and formability (forming rate, cost). In addition, economic problems could be affected by technical developments. Research on new production processes, such as that patented for production from magnesium oxide, could significantly reduce material costs, as could development of economical hot-forming processes. Other promising research areas include study of Mg metal matrix composites and superplastic forming. If these areas are addressed, Mg could become a viable contender for mass production in automotive structures.

If the automotive companies are to increase their use of wrought Mg significantly, they must first witness the successful use of the material elsewhere and conclude that the technology is fully developed. They must also be certain that the material is competitive, and that they can make the substitution without having to write off a significant capital investment prematurely. Such incentives as low-interest loans could be offered to expedite investment in new equipment. Other policy actions (e.g., lower tariffs, stricter CAFE standards) could encourage the use of wrought Mg. Also, a stable price at a level perceived as affordable must be assured.

Two types of action could stimulate the use of Mg in the automotive industry. First, steps could be taken to ensure availability and remove the perception of scarcity and fears of high elasticity of demand. The raw material would then become more cost-competitive on a pound-for-pound basis. Second, a multifaceted R&D program featuring work on new processes for material production and fabrication, including the development and testing of a prototype major component with dramatic mass reduction (e.g., a spaceframe or hybrid frame structure) to highlight Mg's potential, is recommended. Initially, the program would identify the range of problems and opportunities. A more detailed research program, aimed at resolving any problems identified, could follow.

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