Potential Applications of Wrought Magnesium Alloys for Passenger Vehicles

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Abstract

Vehicle weight reduction is one of the major means available for improving automotive fuel efficiency. Although high-strength steels, aluminum (Al), and polymers are already being used to achieve significant weight reductions, substantial additional weight reductions could be achieved by increased use of magnesium (Mg) and its alloys, which have very low density. Magnesium alloys are currently used in relatively small quantities for auto parts; use is generally limited to die castings, such as housings. The Center for Transportation Research at Argonne National Laboratory 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 or aluminum for automotive structural and sheet applications. This study identifies technical and economic barriers to this replacement and suggests R&D areas to enable economical large-volume use. Detailed results of the study will be published at a later date.

Magnesium sheet could be used in body nonstructural and semi-structural applications, while extrusions could be used in such structural applications as spaceframes. Currently, Mg sheet has found limited use in the aerospace industry, where costs are not a major concern. The major barrier to greatly increased automotive use is high cost; two technical R&D areas are identified that could enable major reductions in costs. These are novel reduction technology and better hot-forming technology, possibly operating at lower temperatures and involving superplastic behavior.

1 Introduction

1.1 Rationale for Considering Magnesium

Magnesium (Mg) is an attractive material for use in automobiles, primarily because of its light weight. It is 36% lighter per unit volume than aluminum (Al) and 78% lighter than iron (Fe). When alloyed, Mg has the highest strength-to-weight ratio of all of 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 in an effort to improve fuel efficiency and also to 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.

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. Although U.S. production capacity is underutilized, major increases in automobile usage would eventually require significant expansion of production capacity. Magnesium is also recyclable, and instituting a recycling system as usage increased would serve to extend supplies and also to save energy. This system would need to include careful alloy identification and segregation.

But there are other factors that hinder the widespread use of Mg in automobiles. Although none of these factors is a "show-stopper," the drawbacks have limited the growth of Mg usage. Most are amenable to technical or institutional fixes. The most important factors have to do with the material's physical properties, some of which are less desirable than its low density. Table 1 compares physical properties of Mg with those of Al and Fe. Note, in particular, Mg's lower elastic modulus and higher coefficient of thermal expansion with respect to those of the other metals. 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,

TABLE 1: Physical Properties of Pure Magnesium, Aluminum, and Iron

Property	Magnesium	Aluminum	Iron
Atomic number	12	13	26
Atomic weight	24.32	26.98	58.7
Crystal structure	hcp	fcc	bcc
Density at 20°C (gm/cm^3)	1.74	2.70	7.86
Coeff. of thermal expansion, 20-100°C, (× 10^{-6}/°C)	25.2	23.6	11.7
Elastic modulus (10^6psi)	6.4	10	30
Poisson's ratio	0.35	0.33	0.33
Melting point (°C)	650	660	1536
Boiling point (°C)	1105	2520	2862
Latent heat of fusion (cal/g)	88	94.5	65.5
Specific heat (cal/g · °C)	0.22	0.25	0.11
Volume contraction on solidification (%)	4.2	6.6	2.5 (C steel)
Vapor pressure at melting point (mm Hg)	2.75	$<10^{-7}$	$\sim 10^{-4}$
Thermal conductivity at 20°C [(cal/s · cm^2 · °C)/cm]	0.37	0.53	0.18
Electrical conductivity at 20°C (IACS, %; Cu as 101%)	38	64.9	17.5

development of new alloys has gone a long way toward achieving acceptable properties.

The key factor that inhibits the massive substitution of Mg for other materials in automobiles is its relatively high and unstable price (the average 1993 N.Y. price was $1.48/lb, but prices as low as $0.88/lb were reported). On a per-pound basis in 1993, magnesium cost 3.5-6 times as much as steel and 1.7-2.8 times as much as aluminum (Metal Statistics 1994, 86th edition, American Metal Market, N.Y. 1994). However, 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. In addition, Mg may have lower fabrication and joining costs, substitution by lightweight materials may enable secondary weight savings, and vehicle fuel costs over the car's lifetime are reduced, so the total lifecycle cost of a Mg part may not actually be higher than that of one made from another material.

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 (Fougner 1994). Even if current prices accurately reflect costs, process R&D could significantly reduce the cost of Mg production. Another cost factor in the Mg equation 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, and often operations that require several steps for steel can be done in only one step for Mg. However, because of Mg's crystal structure, fabrication must be done at elevated temperatures (200-315°C), so the large and very capital-intensive machinery in place for fabricating steel parts cannot be used. Considerable investment would be required on the part of automakers if they were to shift to use of Mg for major body parts. However, especially with possible improvements in hot-forming, operating costs could be much lower for Mg parts than for steel parts.

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

Since the impetus for making automobiles lightweight is to save gasoline, it is important to ensure that there is a net energy savings over the lifecycle of the vehicle. As with Al, production of Mg requires large quantities of energy, in the form 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-weight materials in automobiles. For instance, the Volvo LCP 2000, a concept car that used several lightweight materials, including about 50 kg (110 lb) of Mg for the wheels, chassis, and engine block, was estimated to have a lifetime energy consumption, including both vehicle production and use, less than 60% that of an equivalent-sized conventional automobile (Volvo no date). In addition, new, less energy-intensive processes for production are being considered, and savings can be further increased considerably by material recycling at the end of the product's lifecycle.

1.2 Historical Perspective

There is a long history of Mg use in transportation systems. Because of its light weight, Mg has found widespread use in airplane bodies, especially during World War II, when U.S. production capacity peaked sharply. Magnesium has also found application in truck bodies, where a decrease in trailer weight translates into increased carrying capacity and increased revenues that more than offset the higher material cost.

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High stiffness and low density, combined with good strength and excellent dent resistance, make Mg alloys particularly valuable for automobile applications. There has also been considerable interest in use of magnesium in passenger automobiles. Volkswagen produced "Beetles" with Mg engine blocks for many years, using 30,000 tonnes of Mg in 1972. Current production-model cars contain many small Mg castings, averaging around 6 lb/car, with automakers projecting increased use in the future. Some larger parts are in use or being prototyped, such as entire dashboard panels made from a single magnesium casting. Although few sheet or extruded parts are now used, the potential certainly exists. Some of the wrought parts currently under evaluation or in production are listed in Table 2.

1.3 Scope of this Study

Our work explores the possibility of novel applications for Mg, beyond the currently used die castings, in passenger cars. The main interest is in wrought parts, either sheet or extrusions, with novel applications of castings also included. The scope includes possible material modifications to enable the usage, as well as fabrication process or design improvements to make the substitution technically and economically feasible. We adopted a simple, several-step approach. We defined the material requirements for automotive parts, by type of parts, for the three main vehicle systems (body, powertrain, and chassis); characterized the physical properties of Mg and its alloys; and described the processes for production and fabrication. We then discussed possible material and design modifications and the factors to be considered in substitution. Examples provided by the history of Al substitution are examined when appropriate. Finally, we identified potential areas for increased use of wrought Mg in automobiles and the barriers to be overcome before this potential can become reality, and we recommended R&D areas to help remove the barriers.

TABLE 2: Magnesium-Alloy Auto Parts

Application	Form	Mg Alloy
Bumper support beam	Extrusion	AZ31B
Steering-column support	Extrusion	AZ31B
Air-bag channel and end caps	Extrusion	AZ31B
	caps	AM60B
Two-way seat adjuster channel	Extrusion	AZ31B
Seat/channel guide	Extrusion	AZ61A
Electric-motor frame and bell ends	Extrusion	AZ31B
	Bell ends	AZ91D
Tubular bucket seat	Stamping	AZ61A
	Extrusion	AZ31B
Two-piece mini-spare	Stamped center	AZ31B
	Extruded rim section	AZ61A
X-ray cassette (2-piece folder)	Stamping	AZ31B
Valve cover	Deep drawn	AZ31B
Oil pan	Deep drawn	AZ31B
Battery tray	Stamping	AZ31B
Two-piece billet wheels	Spun rim	AZ61A
	Machined center	AZ61A
Forged wheel	Forging	ZK60A
Rolled rims	Formed sheet	AZ61A

Source: L. Barnes, personal communication, Spectrulite Consortium, Inc. (Nov. 16, 1994).

2 Materials Use in Automotive Components

2.1 Material Competition and Selection

The material that yields the lowest finished-part cost generally gets selected. In structural applications, that usually means steel sheet, because of its low raw-material cost and the highly productive (i.e., low labor cost) stamping-plus-spot-welding process employed. Appearance parts are overwhelmingly made from polymers by injection molding, a highly productive, low-scrap process that utilizes the not-so-cheap material very efficiently. Parts with complex geometry are preferably made by a molding process, usually die casting for metals and injection molding or sheet-forming for plastics. Powder metallurgy (sintering) is also gaining acceptance for complex components.

Plastics use for nonstructural applications is expected to expand until other materials have been completely displaced. Steel sheet will remain the preferred material for structural applications *until* mass reduction is a high-priority goal, when light metals (Al or Mg) and/or polymer composites will be the alternatives. However, even in weight-critical applications, use of these materials will at first be restricted to *secondary* structural parts, such as hoods, decklids, and seat frames. Primary structural applications (the bulk of the unibody) will be considered when even higher value is placed on weight reduction. This eventuality is already being seen by Audi, Ford, and others experimenting with Al-intensive vehicles.

This study speculates on future automotive applications for Mg, particularly in wrought form. Currently, practically all Mg applications in car bodies are die castings used on secondary structures, such as steering-wheel frames, steering-column housings, seat frames, and instrument-panel support structures. These parts have gained acceptance over Al (which had already displaced cast iron and other alternatives) primarily because Mg provides a further 30 to 35% mass reduction with very little additional cost. Magnesium die castings are very competitive with Al castings, not only because they require less mass, but also because the lower melting temperature of Mg enables longer mold life and leads to lower process energy. However, as with Al, increased use of castings does not necessarily lead to new applications for wrought forms. The only major use for wrought Al has been the sheet and tubes used in heat exchangers. For either metal, a breakthrough is needed.

Wrought Al or Mg for structural applications (the really big potential in cars) must compete with steel sheet, where the only advantage is weight reduction (Al castings are easier to machine than steel but Al sheet is *more difficult* to form and join than steel). In the 1970s, hoods and decklids, bumpers, and other components were made of wrought Al, sometimes using essentially the same tooling originally designed for steel, when rapid weight reductions were required. As soon as cheaper means (mostly with Al castings) were devised for achieving the same mass reduction, however, these costly applications reverted back to steel. Now that the most cost-effective mass reductions have been achieved (mostly by replacement of steel by plastics and cast Al), engineers are again looking at wrought Al as a replacement for steel sheet in major body components.

Wrought Mg must be formed with the material hot (230-350°C), generally making wrought Mg noncompetitive with steel (or even Al) for automotive applications. Automakers, still reluctant to adopt Al as a major body material, continue to use the costly machinery already in place. Use of Mg would require investment in new equipment that has not even been developed and might not produce a cost-effective mass reduction. Given current economics, therefore, wrought Mg is unlikely to be used as a major material.

However, the economics could change, resulting in considerable potential for wrought Mg as an automotive material. With a density 35% lower than Al and comparable tensile strength, Mg is likely to be competitive in many applications. Although the cost of the basic material is currently somewhat higher than that of Al, the two materials have very similar production processes, and there is no clear economic and/or technical reason why Mg *must* be more expensive. The reasons for the current price differential may be related to the very different competitive situations of the two materials (highly competitive for Al, little competition for Mg) and to the much lower state of development of the Mg industry (U.S. consumption of Mg is 1% that of Al). In addition, new production processes and economic hot-forming could reduce Mg part costs. Therefore, it is possible that Mg could become price-competitive with Al on a per-pound basis, in which case it could experience a dramatic increase in automotive use.

2.2 Major Systems of a Passenger Car

The majority of auto parts and components are made from a relatively 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 component or system groups are the body, the powertrain, and the chassis. The major systems and subsystems, each made primarily of at most of a few types of materials, are shown in Table 3.

TABLE 3: Components in the Three Major Auto Systems

Body	Powertrain	Chassis
unibody	engine	suspension system
closures	engine accessaries	steering system
glass	engine electricals	bumper system
hardware	engine controls	brake system
exterior trim	engine cooling system	front subframe
body electricals	transmission or transaxle	rear subframe
interior trim	clutch (if manual)	fuel storage system
seats	drive line (rear-wheel drive)	chassis electricals
passenger restraint and safety systems	differential	exhaust system
instruments and controls	transfer case (4-wheel drive)	wheels and tires
climate control		

2.2.1 The Body

The body is the single largest system group (over 40% of the total mass), and it includes the single largest component in the vehicle, the body-in-white (b-i-w), which by itself constitutes about 25% of the total vehicle mass. In general, metals (mostly steel) are the first choice for structural components. Plastics and fabrics are used where appearance (and feel) is most important; rubber is used for sealing and damping applications; mechanisms are made primarily from metals (with increasing use of some plastic parts); and most lightly stressed housings are molded from plastics. Stampings and drawings are used to manufacture metal sheet and light plate (including some fine blanking for mechanisms), plastics are injection-molded, metals are die-cast, plastic sheet is thermoformed, and fabrics are cut-and-sewn.

In considering where wrought Mg could be used in auto bodies, another analogy with Al is useful. The ability of both metals to be easily extruded gives them a clear advantage over steel (seamless pipe is as close as steel gets to extruded shapes). Unfortunately, there are few current automotive body applications for extrusions, but this is circular reasoning, because steel cannot be extruded. As the need to reduce body weight continues, extrusions could find increasing applications. Secondary structural parts, such as pillars, roof rails, window frames, and door sills, are obvious possibilities. Entire spaceframes, already made from Al, could also be made from extruded Mg components, or from a mixture of Mg and Al.[1] Considerable mass reduction is potentially

[1] Audi and Alcoa reported advantages of the Al spaceframe, including a weight saving of 35% or more over the traditional steel unibody. This leads to improved fuel economy and reduced emissions without downsizing the vehicle or compromising passenger comfort or safety. Increased stiffness results in improved ride and handling, and tooling expenses and parts inventories are reduced, with more efficient manufacturing and design-to-production schedules. In addition, recycling is economical.

achievable with such a concept, or with a hybrid structure made of some extrusions and some sheet. Advanced, high-volume production and cost-effective manufacturing techniques for Mg alloys, such as thin-wall extrusion, vacuum die casting, precision bending, and high-efficiency joining processes, would be key to the Mg spaceframe.

The limitations introduced by hot forming, the high scrap rate normally associated with fabrication from sheet, and the lack of a well-accepted joining process all make the role for Mg sheet and plate in automotive bodies uncertain. But Mg offers mass reductions beyond those possible with Al. In addition, Mg can be stamped (at high temperature) in a single step into complex shapes, like decklids, that are difficult to produce with Al or steel. A smaller press could be used because of the lower force required to hot-form Mg (compared to stamping steel). If a practical, high-productivity Mg hot-forming process were developed that employed one or two forming steps to achieve the same result as four hits in a current steel press line, it would be very attractive, and perhaps justify its adoption. One precedent for such a decision is the hot-stamped side-impact door beam process (980°C) that Ford recently adopted. It turns 50 ksi (yield strength) steel into 180-200 ksi material, resulting in a better product with a lower cost.

The best potential opportunities for wrought Mg in body components lie with the use of extrusions on primary structures, such as spaceframes. Even if Mg spaceframes do not become economical in the mass market, penetration in the specialty automotive market (50-100,000 units/year) would represent a significant increase in Mg's total usage. There could also be some opportunities for seat frames, where Mg castings are already being used, and a combination of castings, extrusions, and possibly sheet could be competitive. The use of Mg sheet in body panels would require development of an economical, high-volume, hot-forming process.

2.2.2 The Powertrain

The components in the powertrain are markedly different from those in the body. The engine and transmission, which constitute the main mechanical groupings in the vehicle, are characterized by complex assemblies of many individual components. Materials used are highly diverse. Components perform many different functions, ranging from structural to kinematic, fluid handling and control, heating/cooling, lubrication, power transmission, timing, etc.; many of these operations take place under highly stressful conditions caused by high temperatures, rapid motion, friction, high mechanical loads, high fluid pressures, or a combination of these. As a result, the materials used tend to be highly specialized and of high specification.

Within this group, housings are normally cast from Al (recent trend) or iron (older practice). Stressed mechanical components (gears, shafts, etc.) are made from steel bar or forgings, and occasionally from highly engineered stampings or high-grade iron castings (nodular iron, etc.). Covers are made from steel stampings, cast Al or Mg, and molded plastics, and such highly specialized components as engine valves, pistons, transmission clutches, bearings, etc. are often made from a combination of materials, using highly developed, unique processes. For example, engine valves are often made from three separate materials welded together (high-temperature resistance [nickel] alloy for the head, carbon steel for the stem, and high-wear-resistance alloy for the tip), and pistons are made from Al, but with a cast-in steel insert to control expansion. Most of these parts are machined, either from bar stock or from a near-net form made by casting, forging, stamping, and sintering. Machining is usually fully automatic and often of high precision, including extensive grinding and even honing final operations.

Trends in material substitution in this group include an essentially universal replacement of cast iron housings by Al castings, some Mg castings, and, more recently, even plastic moldings; replacement of cast iron (high-temperature alloy) exhaust manifolds with stainless steel (tube) fabrications; replacement of cast iron or forged steel connecting rods with sintered powder metal forms and/or Al forgings; replacement of nodular iron castings in crankshafts with forged low-alloy steel; and finally, replacement of stamped steel covers with Mg castings and/or plastic moldings, including sheet-molding composites. The use of other new material systems cannot yet be considered a trend, but their use is worth noting. Titanium has been proposed for valve-train components (valves, springs, retainers, etc.), and even for connecting rods. Ceramic components are also appearing in some high-temperature applications, such as turbo-charger rotors and diesel-engine prechambers, and they are being considered for some high-wear components. Some components are going through a second level of substitution; for instance, intake manifolds made from cast iron, then replaced by Al castings, are now being replaced by injection-molded nylon (lost-core process).

What are the possibilities for Mg in this component group? Magnesium castings are replacing some of the iron and even Al castings in some housings and covers. However, Mg does not have the same creep resistance as does 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. Although the VW "Beetle" used a Mg crankcase, that was an *air*-cooled engine, where the hot components (i.e., the cylinders) were made of cast iron. 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. Even wrought Al has gained little hold. The physical properties of Mg do not readily suggest many new possibilities; some replacement of castings by stampings in simple covers and other, similar parts is possible, but little else has been proposed. In summary, increased use of Mg in powertrain components is most likely in castings.

2.2.3 The Chassis

The chassis components are highly diverse, but their characteristics lie in between those of the two other groups; the mechanisms they encompass tend to be simpler, and many components also have structural functions. Iron and steel still play a major role among chassis materials. Components with significant structural function, such as the suspension and subframes, are dominated by steel, while those with predominantly mechanical functions, such as the steering and brake systems, include more diverse and specialized materials. Systems with special functions, like the exhaust, electrical system, fuel storage, and tires, require similarly specialized materials. Many of these systems have, during the last decade or so, experienced significant materials substitution, and radically different material options may still be available.

Materials currently used can be summarized simply. Subframes, suspension links, springs and rods, steering links, and some bumper structures are mostly made from steel rod and/or formed sheet (and plate). Polymer composite (epoxy/fiberglass) flat springs have been used in a few vehicles but seem to be less popular now. Housings, as in the steering and brake systems, are made mostly from cast Al, but some cast iron still remains. Mechanical components in the steering rack, shocks, and some brake subsystems are mostly machined from steel. Intricate geometry components, like wheel hubs and steering knuckles, are usually made from cast iron or, more recently, from cast Al. The exhaust system is made from steel, but the need to endure high temperature and corrosion has dictated a number of coatings and protective processes and, in some cases, the use of stainless steel. Fuel-storage systems rely on two materials: tin-coated steel (terne plate) and blow-molded plastics. Wheels are made primarily from stamped/rolled steel or from cast Al. Rubber is the material-of-choice (probably the only choice) for tires, as well as for flexible joints. Bumper systems increasingly depend on polymer foam or molded beehive or egg-crate forms to absorb the energy of collisions. The impact is transferred to the main structure through a bumper beam made from extruded-Al glass-reinforced composite or from stamped steel. Foundation brake components are still predominantly made from cast iron, but Al calipers are becoming more common, and composite Al rotors and drums are being seriously considered. Many of these parts are formed from rod, tube, or sheet/plate, followed by welding, for structural components, and by machining from castings or bar, for the more complex mechanical components.

Some of the most important trends in material substitution include replacement of iron castings with Al, replacement of terne plate fuel tanks with blow-molded plastics (delayed by permeation problems), and the use of polymer-based systems for energy absorption on bumpers. More recently, there has been some replacement of steel with Al castings and/or forgings in the suspension system. Polymer composites are also being considered for the simpler suspension links, using a combination of pultrusion and Al die castings for the attachment ends. Composite flat springs were popular, but coil springs are again being used because of design advantages.

What are the possibilities for Mg in the chassis? Aluminum is gaining share among the housings and other complex castings used in the chassis, and Mg could substitute for many of them, especially in unsprung components, where light mass is key. Wheels were one of the first applications for Mg, and development of a more 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 demonstrated on the experimental Ford "Synthesis" lightweight vehicle. Most new opportunities for Mg use in the chassis group require castings, but the opportunity clearly exists for Mg extrusions to replace fabricated steel components.

2.3 Characterization of Auto Industry

Although there is a significant trend to replace heavier materials, such as iron and steel, with lighter ones, such as plastics and Al, in passenger cars, only a few material systems that have consistently proven to be competitive (cast Al for housings, molded plastics for non-structural components, etc.) account for most of the gains, while others have only a token presence.

What would be required for Mg to become a widely used automotive material? There are two factors that inhibit Mg use by U.S. automakers. The first is the perception that it is in short supply, so that automotive industry use (huge by historical magnesium standards) could drive the price rapidly upward. This problem was addressed in a paper by S. Fougner (CCM 1994). The second problem is that the industry has only just become acquainted with die-cast Mg products. Industry resistance to use of lightweight metals in wrought form is strong because there is little experience with their processing. In addition, there are the limitations caused by the need to hot-form wrought Mg; the process is not popular with U.S. manufacturers. To understand the seriousness of these problems, we must consider the general characteristics of the automotive industry.

The automotive business is primarily a *manufacturing* industry, the key function being high-volume, low-cost production of a complex product at extremely sophisticated and capital-intensive manufacturing facilities. Rapid technical developments that bring early obsolescence for costly production equipment are undesirable. Nor can the industry afford to take the higher risks usually associated with many new technical developments, for when things do not work as expected, the consequent losses can be catastrophic. Therefore, the automotive industry tends to be extremely conservative and to adopt new concepts or processes only after they have been proven safe and effective elsewhere. Most innovation in the automotive industry comes from suppliers, not from the OEMs.

The automotive industry is often criticized as being slow to adopt new technology, particularly when compared with progressive industries like aerospace or electronics, but this comparison is unfair, because the nature of these industries is so different. Aerospace products are often purchased by governments, who may be partners in development, and a main function of that industry is *development*, not manufacturing. The electronics industry, on the other hand, thrives on creating new gadgets that consumers "must" have; when these do not work as expected (which is often), they are thrown away, for they are cheap and will be obsolete next year anyway.

The automotive industry works under a different set of constraints. Vehicles are expensive (second only to housing), durable consumer goods and are expected to have a long, trouble-free life. If they do not, consumers expect to be compensated appropriately — an expectation often encouraged and even enforced by government. The large numbers in which vehicles are produced make fixing "mistakes" a very expensive process. As a result, the automotive industry must be extremely conservative in its adoption of new technology; only well-proven, low-risk innovations are considered.

True R&D activities therefore represent a tiny fraction of the industry's effort; the bulk of the technical resources are devoted to *engineering* a well-proven product for cost-effective, trouble-free production. U.S. automakers should not be expected to invest in R&D to enable the adoption of Mg as a major material in high-volume vehicles. If Mg is ever to attain its potential, the basic research and development needed will have to be done by some other entity that has an interest in the material being adopted.

3 Properties of Magnesium and Its Alloys

Magnesium is readily available commercially at purities of >99.8%, but it is rarely used for engineering applications in its unalloyed form because of its limited mechanical properties and corrosion resistance. The element has a hexagonal close-packed (hcp) lattice structure, and its alloying behavior is notable for the variety of elements with which it will form solid solutions. Alloying additions commonly used in commercial alloys include Al, Zn, Li, Ce, Ag, Zr, and Th, among others.

3.1 Mechanical Properties

The yield and tensile strengths of commercial Mg alloys are comparable with those of Al alloys and can approach those of low-carbon steel. However, the ductility of Mg alloys tends to be somewhat lower than that of Al alloys and is clearly lower than that of low-carbon steel sheet. For Mg castings, the compressive yield strength is approximately equal to the tensile yield strength. For wrought alloys, however, the yield strength in compression may be considerably less than that in tension. The yield and tensile strengths of Mg alloys decrease rather markedly with increasing temperature. The practical upper temperature limit for their use is as low as 120-140°C for Mg-Al-Zn alloys and 150-250°C for Mg–Zn–Zr alloys with rare earth additions. Certain Th-containing alloys exhibit acceptable strengths up to 250-350°C.

The fatigue strength of Mg alloys covers a relatively wide scatter-band, with most alloys exhibiting an endurance limit at 10^7 to 10^8 cycles. The fatigue strengths are higher for wrought products than for cast test bars, and increasing surface smoothness improves resistance to fatigue failure. The fatigue strength of Mg castings is about the same as that of iron castings currently used as structural parts in automobiles.

Magnesium alloys have sufficient hardness for all structural applications except those involving severe abrasion. Although rather wide variations in hardness are observed, the resistance of the alloys to abrasion varies by only about 15 to 20%. Several Mg sheet alloys exhibit a very high resistance to denting.

Magnesium-based alloys containing 0.4–0.6 wt% Zr have wide application as high-damping materials, and high-damping Mg alloys containing Mn and Si are also available. The best Mg casting alloys possess greater damping capacities and are lighter than either cast Fe or the Al alloys.

3.2 Corrosion Resistance and Protection

Magnesium is high in the electrochemical series, but the oxide film normally present on Mg offers considerable surface protection in rural and most industrial environments, and the corrosion rate of Mg typically lies between those of Al and mild steel. The corrosion resistance of a Mg alloy part depends upon the environmental conditions, the chemical composition of the alloy, its thermal and mechanical history, and the surface condition of the part. Galvanic corrosion associated with contact with dissimilar metals is a concern, but, in general, Mg alloys possess sufficient corrosion resistance to be used successfully in a wide variety of commercial applications.

Some Mg alloys may be susceptible to stress corrosion cracking (SCC) if subjected to tensile stress and exposed to distilled water, dilute chlorides, and some other solutions. Cracking is primarily transgranular and appears to show comparatively little relationship to microstructural features, such as slip or twinning planes. Wrought products are more likely to undergo SCC than castings.

It is common practice to protect the surface of Mg and its alloys, and such protection is essential where contact with other metals may lead to galvanic corrosion. The surface protection methods available for Mg alloys include standard paint finishes, vitreous enameling, sealing with epoxy resins, electroplating, fluoride anodizing, electrolytic anodizing, and chemical treatments.

3.3 Flammability and Explosiveness of Magnesium

Combustion of Mg requires that the metal be heated to a temperature high enough to produce sufficient vapor to support combustion. This occurs at or above the melting temperature of ≈650°C. Because the thermal conductivity of Mg is high, an entire massive piece must be raised to very near its melting point for it to burn freely. However, for finely divided Mg, the heat from burning will not be quickly conducted away and combustion will continue. Fires that involve dry, finely divided Mg are typically very slow-burning and slow-spreading, but wet, finely divided Mg burns much more intensely because of H_2 liberation. Fine Mg suspended in air can explode in the presence of an ignition source.

3.4 Crashworthiness of Materials in Automobile Structural Components

The three important sections of a vehicle for crash energy management are the front, the rear, and the passenger compartment. The forward and rear sections, located away from the passenger compartment, are intended to be collapse/crush zones. The main function, during collision, for the structural components in these zones is to provide maximum energy absorption of kinetic energy. The energy absorption is the product of force and displacement (i.e., the work done on the structure). Thus, the elements designed to serve as energy absorbers should have the ability to undergo large plastic deformations, using materials exhibiting *high ductility* and low tendency to fracture at low strains (<30-40%). Materials with poor ductility could exhibit fracture or material separation, leading to poor energy management.

The passenger compartment must exhibit high structural integrity, especially during side and rollover (roof crash) collisions. The crush characteristics of theload-carrying (load path) members of the compartment structure should, therefore, reflect high crush resistance and absence of collapse mechanisms that are accompanied by a catastrophic reduction in load-carrying capacity. The limiting factor is the *yield strength*, consistent with manufacturing limitations.

Magnesium alloys possess higher specific strength than do Al alloys and steels. For equivalent crush-loading capability, Mg extrusions exhibit higher potential than do Al extrusions for weight reduction. Due to Mg's low density (and high specific strength), a thicker rail can be made of Mg that possesses the same crush-loading capacity as a steel rail, with less weight penalty than one made of Al extrusions. However, as with Al, Mg alloys exhibit lower energy-absorption capability (lower elongation) than steel for the same geometry.

Current fabrication for steel rails forms a flat plate into a square column and spot welds it along its full length, although seam welding is now also being considered. Many automotive components are made from sheet components spot welded together at flanges. When these components are subjected to a crush load, the elements between the spot welds may separate and reduce the efficiency of the crush. Adhesive material is sometimes added to overcome this problem. Another alternative is to use extruded rails instead of ones joined by welding. This option provides an advantage for both Mg and Al alloys. Crush behavior of extruded Mg rails is an area for R&D to address.

4 Magnesium Production

Magnesium is the eighth most abundant element in the earth's crust, but it never occurs naturally in the uncombined state. Several Mg-containing minerals are commonly found in the earth's crust, but dissolved Mg in seawater is now the main source of the metal. The three methods presently used to produce Mg are (1) the electrolytic reduction of $MgCl_2$; (2) the Pidgeon process, in which dolomite is directly reduced at high temperatures in the solid state; and (3) the Magnetherme non-electrolytic process, carried out with the reactants in the liquid state.

A potentially more economical method for electrolytic production of Mg, using magnesium oxide as the feedstock, has recently been developed. The method uses a rare-earth chloride as a constituent of the electrolyte. This chloride spontaneously reacts with the MgO to form $MgCl_2$, which is then electrolyzed by standard methods, and the rare-earth oxychloride. The rare-earth oxychloride is destroyed electrolytically to regenerate the chloride (Sharma 1994). Development of this process could potentially reduce the cost of Mg as a raw material and greatly improve its competitive position.

4.1 Fabrication of Primary Shapes

Sand and permanent-mold castings can be used to fabricate extremely intricate shapes, and the relevant mechanical properties of Mg casting alloys are competitive with those of other materials. Sand casting is only suitable for low-volume production due to the slow cooling rate, but permanent castings can be produced in high volume. Alloys have been developed that exhibit not only good mechanical properties, but also excellent castability and good resistance to microshrinkage.

The Mg–Al–Zn alloys are normally used for die castings. Cold-chamber machines are used for the largest castings, but hot-chamber machines, which cannot be used for Al alloys, are used for most Mg die casting applications and are more competitive for smaller sizes. For these applications, magnesium alloys offer the advantages of (1) high fluidity, (2) low specific heat per unit volume, (3) high gate pressures at moderate injection pressures, and (4) a low solubility for Fe from the dies.

Wrought Mg-alloy products are produced mainly by rolling, extrusion, and press forging at temperatures in the range 300–500°C, since the hcp crystal structure of Mg places limitations on the amount of deformation that can be tolerated at lower temperatures. Rolling and extrusion tend to produce preferred orientations in Mg alloys, and twinning under compressive stresses tends to reduce the compressive strength, thereby reducing resistance to compressive buckling. Wrought Mg products are not currently used in automotive applications. Rolled Mg alloy products include flat sheet and plate, coiled sheet, tooling plate, tread plate, and photo-engraving plate. Mg-Al-Zn alloys are widely used for rolled sheet applications near room temperature; these alloys can be strengthened by strain hardening and are weldable. The Mg-Li system has attracted attention as a basis for very lightweight sheet and plate, with other alloying additions typically required to achieve thermal stability and weldability.

Extrusion is the most commonly used wrought process for Mg alloys. The quality and production rate are affected by the geometry and complexity of the shape, the reduction in area, the alloy being used, the extrusion temperature, and the design of the die. Most Mg extrusions undergo secondary operations before the final part is complete. A number of Mg extrusion alloys are in common use, and Mg extrusions have been used for many transportation applications.

Forgings represent a relatively small percentage of wrought Mg products and are generally used where lightweight parts of intricate shape are required with strengths higher than those that can be achieved with castings. Magnesium is one of the easier materials to forge, so the number of forging operations needed to produce finished parts can be greatly reduced. Press forging is more common than hammer forging, but commercial alloys have been developed for both operations.

Metal matrix composites (MMCs) offer the potential for tailored mechanical, physical, and thermal properties, and Mg MMCs exhibit higher weight-reduction potential than do Al and Ti MMCs. However, due to the perceived inferior physical/chemical and mechanical behaviors of Mg alloys, R&D on Mg MMCs has not received great attention. Nevertheless, various combinations of Mg alloys reinforced with ceramic particles or graphite are being investigated for such automotive applications as driveshafts in trucks, body structures, brake rotors and calipers for brake systems, and engine blocks. This work offers considerable potential for automotive applications.

4.2 Secondary Forming of Wrought Products

The secondary forming of Mg alloys includes such operations as bending, deep drawing, rubber forming, dimpling, stretch forming, spinning, and impact extrusion. Magnesium alloys are usually formed at elevated temperatures, but the methods and equipment used in forming these alloys are similar to those commonly employed in forming alloys of other metals. Working of Mg at elevated temperatures has several advantages over cold working. The processes used to form wrought Mg include bending, deep drawing, rubber forming (or hydroforming), stretch forming, spinning, and impact extrusion.

Superplastic forming is used to fabricate a wide range of parts, but Mg alloys have received relatively little attention in superplasticity research. Most studies have focused on Mg-Li alloys possessing two-phase microstructures and on alloys containing rare-earth elements that produce finely dispersed precipitates that can stabilize a fine grain structure during superplastic deformation. Equal-channel angular extrusion can also be used to produce a favorable fine-grain structure. More work is needed on the development of superplastic processes at lower temperatures and higher strain rates, the effect of superplastic processes on mechanical properties, and the superplastic forming of conventional wrought Mg alloys. This development could greatly lower the cost of Mg auto part production.

Magnesium and its alloys are among the most machinable of all structural materials. An outstanding machining characteristic of Mg alloys is their ability to acquire an extremely fine finish; subsequent grinding and polishing is often unnecessary. Distortion of Mg parts during machining rarely occurs and usually can be attributed to excessive heating or improper chucking or clamping. Most machining of Mg alloys is done dry, but cutting fluids sometimes are used for cooling.

4.3 Joining

Virtually all Mg welding is done with the inert-gas-shielded tungsten arc (TIG) or consumable electrode (MIG) processes. Rods of approximately the same composition as the base metal are generally satisfactory for the arc welding of Mg alloys. Arc-welded joints in annealed Mg-alloy sheet and plate have room-temperature tensile strengths only slightly lower than those of the base metal, but the strengths of arc welds in hard-rolled material are significantly lower than those of the base metal because of annealing effects. Arc welds in some Mg alloys are subject to stress corrosion cracking, and thermal treatment must be used to relieve residual stresses. Wrought Mg and Al alloys can be spot welded, but castings are not normally resistance welded. Spot welds in Mg have good static strength, but fatigue strength is lower than for either riveted or adhesive-bonded joints.

Brazing is possible for some Mg alloys and may have limited nonstructural automotive applications. The recommended method is dip brazing, although furnace or torch brazing is also possible. Because brazing is carried out at a high temperature, there is significant property degradation. Soldering is not generally used for making structural joints in Mg alloys, though it can be used for special purposes, including the filling of dents, seams, and surface irregularities prior to painting.

Adhesive bonding of Mg is an important fabrication technique, especially suited for those applications that require good fatigue strength. Adhesive bonding also permits the use of thinner materials than can be effectively riveted. The extensive development that has occurred in adhesive technology has resulted in a wide choice of adhesive types, strengths, and application methods. Mechanical joints include rivets, screws, bolts, self-clinching devices, and interference fits. Magnesium is not suitable for the joining material, such as a bolt or rivet, and a common factor in all mechanical joints for Mg is the use of a dissimilar metal and the attendant possible galvanic corrosion effects.

4.4 Magnesium Recycling

Recycling is possible for waste materials generated throughout a Mg product's lifecycle, from slags produced during smelting to worn-out auto parts. Recycling reduces the impacts of waste and recovers useful financial value or energy content from the material. More value is generally recovered from materials reused as close to the final stage as possible, so that as few costly and energy-intensive steps as possible need to be repeated. For Mg, we are particularly concerned with recovering materials that have undergone reduction (i.e., fabrication scrap and post-consumer material), either from part replacement or, more likely, from scrapping of the entire automobile at the end of its useful life.

4.4.1 Recycling in the Manufacturing Process

There are two main types of scrap in manufacturing operations: home scrap and prompt scrap. The first, generated during cleaning or trimming operations at a plant, is available for remelting (perhaps with a refining step) on-site. This is the easiest category to deal with, because its composition is well-known and it can immediately reenter the flow with no degradation in purity and properties. Prompt scrap is generated during fabrication operations, such as casting, which may leave as much as 50% of the material in runners and other trimmings, and stamping, which typically leaves 25% or more of the material around the useful shapes. Although this material could be treated as home scrap and remelted on-site (as is often done in high-volume iron and steel fabrication), for Mg it is generally sold to a secondary smelter, who then remelts and refines it for resale. Volkswagen remelted its own casting scrap from Mg blocks, melting 7.4 lb of its own scrap in every 100 lb of ingot. The secondary smelter handles scrap from numerous fabricators and therefore deals with a variety of alloys. If the optimal properties designed into specific alloys are to be maintained, these alloys must be sorted to keep them separate during recycling, or at least mixed only to the extent that they are compatible. Otherwise, the properties will be degraded, and a lower-valued product will result ("down-cycling").

The infrastructure for recycling of Mg manufacturing scrap is not highly developed. The fact that the U.S. Department of Transportation regulates Mg scrap as a flammable material (appropriate for cuttings and chips only) is a factor deterring development. In 1992, secondary production represented only 29% of total U.S. production, and much of that was in the form of an alloying element in Al can stock. Considerable potential exists for increasing the quantity of industrial Mg scrap recycling.

4.4.2 Recycling of Post-Consumer Magnesium Scrap

There is very little recycling, per se, of obsolete Mg from automobiles at this time. The main reason is the economics. The cars now being scrapped average about 10 years old, so the quantity of Mg in them is small. The parts are not valuable enough to strip out of a hulk before it goes to a shredder. Therefore, the material ends up mixed with Al and copper in the nonferrous stream at the end of the shredding and separation processes. It would be possible to separate the Mg from the other nonferrous metals in a sink/float operation, if sufficient quantities were present, or even manually. However, at the current time, little enough Mg is present that it can simply be left as an alloying element in the recycled Al.

In the future, large Mg parts could be stripped from the hulk before shredding; the Volkswagen Beetle's Mg engine block was removed for recycling. Shredded Mg could be separated from shredded Al. The recovered

Mg could then either be separated into compatible alloy groups or be used for applications with less demanding composition requirements. Parts could be marked to show composition, or a computer database could be available to identify materials for a given part and model. Development of an automated system would be useful, as would definitive work on alloy compatibility.

5 Conclusions

5.1 Research Needs

The technical problems associated with the manufacture of wrought Mg components can certainly be addressed by research. A program to prototype and test a Mg spaceframe or novel hybrid structure, for instance, could become the focus of a number of process-related studies (forming, joining, etc.), bringing immediate attention to an underutilized material. Such a structure could form the core of a super-lightweight body for the "supercar," and it would have a good chance of reaching the 40% mass reduction target. This goal appears too optimistic for an Al-intensive vehicle, and though it is probably technically possible with advanced composites, the economics are currently unattractive. But 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, and some types of suspension system components.

Many technical questions about Mg manufacturing remain, particularly in terms of high-volume production, such as corrosion (galvanic), spot welding, adhesive bonding, and formability (forming rate, cost). In addition, there are key economic problems that could be affected by technical developments. These include high material and manufacturing cost with conventional high-volume production processes. Research on new production processes, such as that patented for production from magnesium oxide, could significantly reduce the material cost. So could development of economical hot-forming processes. Good information on alloy compatibility for recycling could also affect Mg economics. If these areas are addressed, Mg could become a viable contender for mass production in automotive structures.

Additional promising research areas that could potentially enable increased automotive use of wrought Mg include study of Mg MMCs and superplastic forming (possibly using equal-channel angular extrusion).

5.2 Other Barriers

For the automotive companies to increase their use of wrought Mg significantly, it appears that they must first witness the successful use of the material elsewhere, and then conclude that the technology for use is fully developed and ready for adoption. Furthermore, they must be convinced that the material is competitive with other material systems and that they can make the substitution without having to write off a significant capital investment prematurely. Such incentives as low-interest loans could conceivably be offered to encourage investment in the required new equipment.

What policy actions could be taken to expedite the acceptance of wrought Mg by the automotive industry? Current tariffs should be examined to determine if they are appropriate. In addition, a price that is stable at a level perceived as affordable must be assured. Another possible policy alternative that would encourage the use of Mg in automobiles would be stricter CAFE standards imposed by the government. These would force manufacturers to use lighter materials even if they were not cost-competitive.

5.3 Summary and Recommendations

In summary, two types of action could stimulate the use of Mg in the automotive industry. First, steps need to be taken to assure availability and remove the perception of scarcity and fears of high elasticity of demand. The raw material must become more cost-competitive on a pound-for-pound basis. Second, a multi-faceted R&D program is recommended. It would feature work on new processes for material production and fabrication and would include the development and testing of a prototype major component with dramatic mass reduction, preferably one associated with the PNGV program (a spaceframe or hybrid frame structure would be ideal), to highlight Mg's potential. Such a program would identify the range of problems and opportunities. A more detailed research program aimed at resolving any problems identified could then be established.

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