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Analysis of the Potential for New Automotive Uses of Wrought Magnesium

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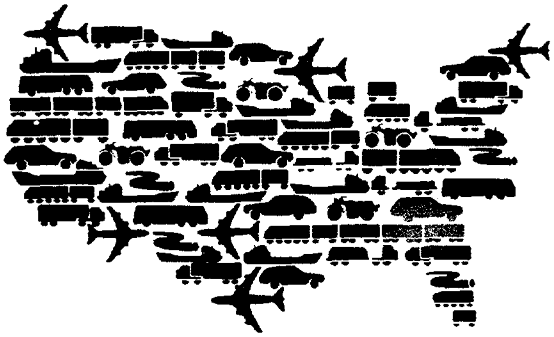

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Analysis of the Potential for New Automotive Uses of Wrought Magnesium

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ANALYSIS OF THE POTENTIAL FOR NEW AUTOMOTIVE USES OF WROUGHT MAGNESIUM

by

L. Gaines, R. Cuenca, F. Stodolsky, and S. Wu

ABSTRACT

The Center for Transportation Research at Argonne National Laboratory has performed a study for the Lightweight Materials Program within the U.S. Department of Energy's Office of Transportation Materials to evaluate the suitability of wrought magnesium and its alloys to replace steel or aluminum for automotive structural and sheet applications. Vehicle weight reduction is one of the major means available for improving automotive fuel efficiency. Although high-strength steels, Al, and polymers are already being used to achieve significant weight reductions, substantial additional weight reductions could be achieved by increased use of Mg (whose density is less than one-fourth that of steel and only two-thirds that of Al). Magnesium die castings are currently used in American-built automobiles and trucks to the extent of ≈4 lb per vehicle but there is no significant use of Mg wrought products for such purposes.

This study shows that Mg sheet could be used in automotive body nonstructural and semistructural applications, whereas extrusions could be used in such structural applications as spaceframes. The primary barrier to such uses of wrought Mg is high cost, which has three contributing causes:

1. Magnesium ingot prices usually exceed those of Al by more than the "two-to-three" relative density of the two metals.

2. Rolling costs are greatly in favor of Al for sheet (plate and extrusion costs are comparable).

3. Magnesium parts must usually be formed hot, and may require corrosion protection, thus adding to the final cost.

These barriers and others are discussed and recommendations are made for R&D to surmount them and to enable economical large-volume use of Mg wrought products.

EXECUTIVE SUMMARY

INTRODUCTION

In this report, we consider 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 includes possible material modifications, as well as process or design improvements to make the substitution of Mg for other materials technically and economically feasible. We define the material requirements for parts in each of the main vehicle systems, characterize the properties of Mg and its alloys, and describe Mg production and fabrication processes. We then discuss possible material and design modifications, and factors that are relevant to proposed substitutions. Examples provided by the history of Al substitution are examined when appropriate. Finally, we identify potential areas for increased automotive use of wrought Mg and recommend R&D to overcome the remaining barriers to such use.

Magnesium is an attractive material for use in automobiles, primarily because of its light weight. It is 36% lighter per unit volume than Al, and 78% lighter than Fe. When alloyed, Mg has the highest strength-to-weight ratio of all 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 downsizing, new design (such as cab forward and front-wheel drive), and shifts to lighter materials. The most striking material shifts have been from Fe to high-strength steel, and from Fe 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 Fe and steel. Current production-model cars contain many small Mg castings, averaging 4.2 lb/car, with increased use projected.

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

Several drawbacks have limited the growth of Mg usage in automobiles. Most are amenable to technical or institutional correction. The most important factors relate to the material's physical properties, some of which are less desirable than its low density. Magnesium is very reactive, but can be protected with applied coatings or simply allowed to build up a naturally occurring protective oxide or sulfate coating. Corrosion has also been a concern, but development of new alloys has advanced significantly toward providing acceptable properties.

The key factor that inhibits massive use of Mg is its relatively high price. On a per-pound basis, Mg costs 3.5-6 times as much as steel and 1.6-2.1 times as much as Al.* However, on a volume basis, the differential is significantly reduced, with the price of Mg varying from even with to 30% above that of Al and from 20% below to 30% above that of steel. In addition, Mg is easy to form, and operations that require several steps for steel can often be done in only one step with Mg. However, because of its crystal structure, Mg must be fabricated at elevated temperatures (200-315°C); thus, the large and very capital-intensive machinery that is in place to fabricate steel parts cannot be used and a significant investment would be required if automakers were to shift to Mg for major body parts. However, operating costs could be lower, and overall, the cost of fabricating and joining may be lower for Mg than for steel parts. In addition, because substitution by lightweight materials enables secondary weight savings and lifetime fuel cost reduction the total life cycle cost of an Mg part may actually be lower than that of one made from another material.

The price of Mg may not represent its true production cost because of lack of competition in the industry, but even if the current price accurately reflects the cost, process R&D could significantly reduce the cost. Another price factor is tariffs, which raise the cost of material imported to the U.S. market. Therefore, although Mg is currently more expensive than its competitors, its relative position can be improved.

Safety in fabrication and use is an 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. 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.

Because the impetus to produce lighter weight automobiles is to save fuel, it is important to be sure that there is a net energy savings over the life cycle of a vehicle. Although Mg requires large quantities of electricity to produce, there is, indeed, a net energy savings by substituting lighter materials in automobiles. Volvo's concept car utilized several lightweight materials, including ≈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) <60% that of an equivalent-sized conventional automobile.** 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.

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*Metal Statistics 1995, 87th ed., American Metal Market, New York.

**Volvo (no date). Volvo LCP 2000 Light Component Project: An International Study for Advanced Technology, Design, and Materials Development, Göteborg, Sweden.

POSSIBLE MAGNESIUM USE IN AUTOMOBILES

The simplest approach to possible uses of Mg in automobiles 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 of an automobile are the body, the powertrain, and the chassis. The major systems and subsystems are each made primarily of, at most, a few types of materials.

The body is the single largest system (>40% of the total mass). Metals (mostly steel) are the first choice for structural components, and mechanisms are made primarily from metals (with use of some plastic parts increasing); most lightly-stressed housings are molded from plastics. The best opportunities for wrought Mg in the body lie with the use of extrusions for primary structures, such as spaceframes. Even if Mg spaceframes do not become economical in the mass market, penetration in the specialty automotive market would represent a significant increase in the use of Mg. There could also be 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.

The components in the powertrain are markedly different from those in the body. The engine and transmission constitute the main mechanical groupings in the vehicle, and are characterized by complex assemblies of many individual components. A great diversity of materials is used. Magnesium castings are replacing some of the Fe and even Al castings in housings and covers. However, Mg does not have the same creep resistance as Al, and therefore 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.

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. Components with significant structural function, such as 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. Aluminum is gaining share among chassis housings and other complex castings, and Mg could substitute for many of them, 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 demonstrated on the lightweight experimental Ford "Synthesis."

PROPERTIES OF MG AND ITS ALLOYS

High-purity Mg is readily available, but it is rarely used for engineering applications in its unalloyed form because of its limited mechanical properties and corrosion resistance. Its alloying behavior is notable for the variety of elements with which it forms solid solutions.

The yield and tensile strength of commercial Mg alloys is comparable to that of Al alloys and can approach that of low-C steel. However, their ductility is somewhat lower than that of Al alloys and is clearly lower than that of low-C steel sheet. The compressive yield strength of Mg castings is approximately equal to the tensile yield strength. However, the yield strength of wrought alloys may be significantly lower in compression than in tension. The yield and tensile strength of Mg alloys decreases with increasing temperature.

Magnesium alloys possess greater specific strength than Al alloys and steels. For equivalent crush-loading capability, Mg extrusions exhibit higher potential for weight reduction than Al extrusions. Because its density is low (and specific strength high), Mg can be used to make a thicker rail that exhibits 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 of the same geometry. Use of extruded rails instead of ones joined by welding would provide an advantage for both Mg and Al alloys. Crush behavior of extruded Mg rails is an area for R&D.

The fatigue strength scatter bands of Mg alloys are relatively wide, with those of wrought products being higher than those of cast test bars. The fatigue strength of Mg castings is about the same as that of iron castings that are currently used as structural parts in automobiles. Magnesium alloys are sufficiently hard for all structural applications except those that involve severe abrasion. Several Mg sheet alloys exhibit a very high resistance to denting. The damping capacity of the best Mg casting alloys is greater than that of either cast Fe or the Al alloys, and the Mg alloys are lighter.

Magnesium is high in the electrochemical series, but the oxide film normally present on Mg offers significant surface protection in rural and most industrial environments, and the corrosion rate of Mg typically lies between that of Al and mild steel. The corrosion resistance of an 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 are sufficiently corrosion resistant 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. 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.

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 its 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, the heat from burning finely divided Mg will not be quickly conducted away and combustion will continue.

MAGNESIUM PRODUCTION

Magnesium is the eighth most abundant element in the earth's crust, but it never occurs naturally in the uncombined state. Although several Mg-containing minerals are commonly found in the earth's crust, the metal is now produced electrolytically from $MgCl_2$ in seawater. A potentially more economical method for electrolytic production of Mg, in which MgO is the feedstock, has recently been developed. Development of such a process could potentially reduce the cost of Mg as a raw material and improve its competitive position.

Wrought Mg alloy products are produced by rolling, extrusion, and press forging. 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. Rolled Mg alloy products include flat sheet and plate, coiled sheet, tooling plate, tread plate, and photoengraving plate. Extrusion is the process most commonly used to produce wrought 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. Forgings represent a relatively small percentage of wrought Mg products and are generally used where an intricately shaped lightweight part with strength greater than that achievable with castings is required.

Metal matrix composites (MMCs) offer the potential for tailored mechanical, physical, and thermal properties, and Mg MMCs exhibit greater weight reduction potential than Al and Ti MMCs. However, because the physical/chemical and mechanical behavior of Mg alloys is perceived as inferior, R&D on Mg MMCs has not received great attention.

The secondary forming of Mg alloys includes operations such as bending, deep drawing, rubber forming, dimpling, stretch forming, spinning, and impact extrusion. The methods and equipment used in forming these alloys are similar to those commonly employed to form alloys of other metals. Working of Mg at elevated temperatures has several advantages over cold working. Superplastic forming is used to fabricate a wide range of parts, but Mg alloys have received relatively little attention in superplasticity research. Equal-channel angular extrusion can also be used to produce a favorable fine-grained 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.

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 that of either riveted or adhesive-bonded joints. Brazing is possible for some Mg alloys and may have limited nonstructural automotive applications. Soldering is not generally used to make structural joints in Mg alloys, although 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. Mechanical joints include rivets, screws, bolts, self-clinching devices, and interference fits. Magnesium is not a suitable joining material, i.e., 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.

Recycling of waste materials generated throughout an Mg product's life cycle is possible, from slags produced during smelting to worn-out auto parts. Recycling reduces the impact of waste and recovers useful financial value or energy content from the material. Industrial Mg scrap is generally sold to a secondary smelter, who then remelts and refines it for resale. The secondary smelter handles scrap from numerous fabricators, and therefore deals with a variety of alloys. To maintain the optimum properties designed into specific alloys, they must be sorted to keep them separate during recycling, or at least only mixed to the extent that they are compatible. Otherwise, the properties will be degraded, and a product of lower value will be the result ("downcycling"). The infrastructure for recycling of Mg manufacturing scrap is not highly developed. 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. Thus, there is significant potential to increase the quantity of industrial Mg scrap recycling.

Because of economics, very little Mg per se is currently recycled from scrapped automobiles. The cars now being scrapped average ≈10 years old, and the quantity of Mg is too small to warrant stripping it from a hulk before it goes to a shredder, but parts could be removed in the future. Therefore, currently, the material ends up mixed with Al and Cu in the nonferrous stream. It would be possible to separate the Mg from the other nonferrous metals either manually, or in a sink/float operation if sufficient quantities were present. However, the little Mg present now can just be left as an alloying element in recycled Al.

CONCLUSIONS

There is significant potential for new automotive uses of Mg; these are summarized in the table below. The technical problems associated with the manufacture of wrought Mg components can certainly be addressed by research. A program to prototype and test an Mg spaceframe or novel hybrid structure, for example, could become the focus of a number of process-related studies (forming, joining, etc.), and bring 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 too optimistic for an Al-intensive vehicle, and while probably technically possible with advanced composites, the economics are currently unattractive. But the economics of an Mg-intensive body (perhaps one that includes 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 suspension system components.

Remaining technical questions about high-volume Mg manufacturing concern galvanic corrosion, spot welding, adhesive bonding, and forming rate. In addition, there are economic problems that could be affected by technical developments. Research on new production processes, such as that patented for production from MgO, could significantly reduce the material cost. So could development of economical hot-forming processes. Additional promising research areas include study of Mg MMCs and superplastic forming. If these areas are addressed, Mg could be a viable contender for use in the mass production of automotive structures.

For automotive companies 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 convinced that the material is competitive, and that they can make substitutions without having to write off significant capital investments prematurely. Incentives, such as low-interest loans, could be offered to expedite investment in new equipment. Other possible policy actions to encourage the use of wrought Mg include reconsideration of current tariffs, ensuring a stable price, and stricter corporate average fleet economy (CAFE) standards.

Summary of potential uses of Mg in automotive industry

Form	Body	Powertrain	Chassis
Extrusions	Spaceframe, seat frames	–	Suspension links, wheels
Hot-formed sheet	Body panels	–	Wheels
Castings	Spaceframe with extrusions, seat frames	Main transmission housing	Housings and other complex castings

1 INTRODUCTION

1.1 BACKGROUND

Magnesium is abundant, with seawater (the main source of supply) representing a virtually unlimited supply. The world's two largest producers, Dow Chemical Company (USA) and Norsk Hydro (Norway), both use an electrolytic process to obtain Mg from $MgCl_2$. Several other countries are also Mg producers. The worldwide production in 1994 was ≈400,000 metric tons, or ≈2% of the quantity of Al produced. Although U.S. production capacity has historically been underutilized, it is less so since Dow closed part of its plant in Freeport, Texas and major increases in automobile usage could eventually require significant expansion of production capacity. Magnesium is also recyclable, and instituting a recycling system as usage increases would extend supplies and also save energy.

Magnesium and its alloys are used in a wide variety of structural and nonstructural applications. The main nonstructural use is as an alloying element in Al, especially for can production (Mg additions improve the corrosion resistance of Al while providing solid-solution strengthening.), with some use in Zn, Pb, and other nonferrous metals. Magnesium is also used as an O_2 scavenger and desulfurizer of Ni and Cu alloys, a desulfurizer in the Fe and steel industry, and a reducing agent in the production of Be, Ti, Zr, Hf, and U. It is also used to protect other metals from cathodic corrosion and in construction of dry-cell and reserve-cell batteries. Because of its rapid but controllable response to etching and its light weight, Mg is used increasingly in photoengraving. Structural applications include components for industrial, materials-handling, automotive, and aerospace equipment. In industrial machinery, such as textile and printing equipment, Mg alloys are used for parts that operate at high speeds and must be lightweight to minimize inertial forces. Materials-handling equipment applications include dockboards, grain shovels, and lawnmower decks. Table 1 shows Mg use for various applications in 1994.

1.2 RATIONALE FOR CONSIDERING MAGNESIUM IN AUTOMOTIVE USES

Magnesium is an attractive material for use in automobiles, primarily because of its light weight. It is 36% lighter per unit volume than Al and 78% lighter than Fe. When alloyed, the strength-to-weight ratio of Mg is the highest 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 reduce emissions. Cars have been made lighter by a combination of downsizing, new design (such as cab forward and front-wheel drive), and shifts to lighter materials. The changing mix of materials in automobiles manufactured in the U.S. is shown in Figure 1. The most striking material shifts have been from Fe to high-strength steel and from Fe

Table 1. 1994 magnesium use in North America (Source: IMA 1994).

Use	% of total
Alloying element in Al	47.5
Structural	
Casting (predominantly die castings)	15.7
Wrought products	4
Electrochemical	4.5
Steel desulfurization	17.6
Cast iron nodularization	4.5
Reduction agent (Ti, Zr, Be, U)	4
Chemical (pyrotechnic application)	1
Other	1.2

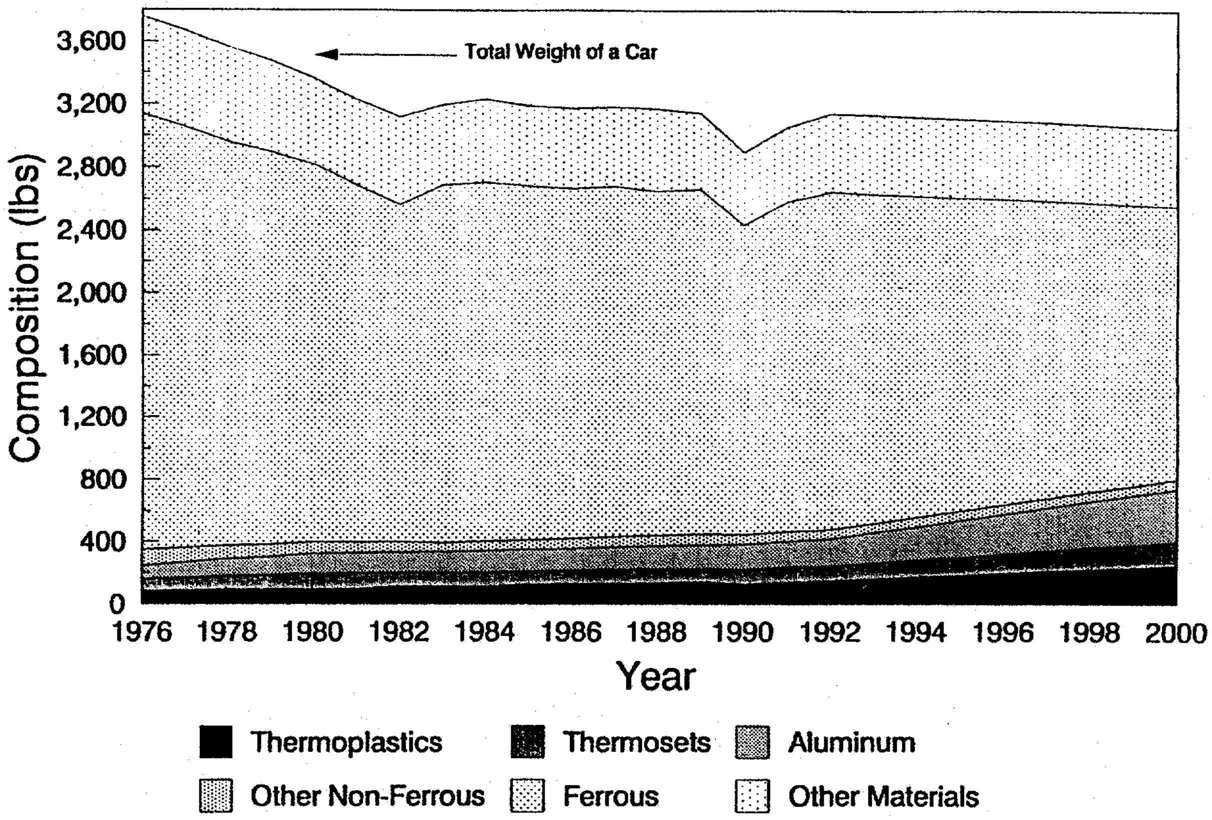


Figure 1. Automobile material composition vs. time (Source: Curlee 1994)

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 in uses already taken over from Fe and steel.

However, there are several 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 resolution. The most important have to do with the material's physical properties, some of which are less desirable than its low density. Table 2 presents the 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 and corrosion has been a concern; however, it can be protected with applied coatings or by simply allowing it to build up a naturally occurring oxide or sulfate coating. In addition, development of new alloys has made significant contributions toward achieving acceptable properties.

The key factor that inhibits the massive substitution of Mg for other materials in automobiles is its relatively high price. The price is somewhat variable (the 1994 average free-market price was \$1.03-\$1.38/lb), but less so than that of Al, whereas alloy prices are more stable. On a per-pound basis in 1994, Mg cost 3.5-6 times as much as steel and 1.6-2.1 times as much as Al (American Metal Market 1995), although producers aim for price equality with Al. However, on a volume basis, the differential is considerably less, with the price of Mg varying from the same as to 30% above that of Al and from 5% below to 20% above that of steel (Metal Statistics 1995). In addition, fabrication and joining costs of Mg may be lower, substitution by lightweight materials may enable secondary weight savings, and vehicle fuel costs over the lifetime of a car would be reduced. Thus, the total life cycle cost of an Mg part may be lower than that of one made from another material.

Another concern is 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. A potential concern is that there is currently only one source of wrought Mg products. This situation would presumably be corrected if a significant demand were perceived. Tariffs, another factor in the costs of Mg, raise the cost of imported material, especially when it comes from countries that are not most-favored nations in the U.S. market. (Table 3 shows 1992 rates, but these are still current in 1996 [Kramer 1996]). In addition, antidumping duties have been imposed on Mg imported from Canada, China, Russia, and Ukraine. These duties have had an even more significant impact on prices (Kramer 1996). 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 require only one step for Mg.

Table 2. Physical properties of pure magnesium, aluminum, and iron (Source: ASM 1983)

Property	Magnesium	Aluminum	Iron	C steel
Atomic number	12	13	26	-
Atomic weight	24.32	26.98	58.7	-
Crystal structure	hcp	fcc	bcc	-
Density at 20°C (g/cm^3)	1.74	2.70	7.86	-
Coeff. 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	-
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	-
Vapor pressure at melting point (mm Hg)	2.75	$<10^{-7}$	-	$\approx 10^{-4}$
Thermal conductivity at 20°C [(cal/s cm$^2\cdot$°C)/cm]	0.37	0.53	-	0.18
Electrical conductivity at 20°C (IACS, %; Cu as 101%)	38	64.9	-	17.5

However, because of Mg's crystal structure, fabrication must be performed at elevated temperatures (200-315°C), so the large, very capital-intensive machinery that is in place for fabricating steel parts cannot be used. Significant investment would be required on the part of automakers if they were to shift to 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 during fabrication and in use is an important, but often overstated, concern. Magnesium is perceived to be highly flammable; 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 thick would cease burning when the heat source is removed. Appropriate safety precautions are required during machining. Another safety issue concerns the impact resistance of Mg structures; however, with careful design, crash safety standards can be maintained with Mg structures.

Table 3. U.S. import duties, 1992 (Source: Minerals Yearbook 1992)

Item	Most-favored nation (MFN) Jan. 1, 1992	Non-MFN Jan. 1, 1992
Magnesium		
Unwrought magnesium	8.0% ad valorem	100% ad valorem
Unwrought magnesium alloys	6.5% ad valorem	60.5% ad valorem
Magnesium waste and scrap	Free	Free
Wrought magnesium	14.8 cents per kilogram on Mg content + 3.5% ad valorem	88 cents per kilogram on Mg content + 20.0% ad valorem
Magnesium compounds		
Crude magnesite	Free	$10.33 per ton
Dead-burned and fused magnesia	0.4 cent per kilogram	1.7 cents per kilogram
Caustic-calcined magnesia	$2.07 per ton	$20.70 per ton
Other magnesia	Free	15.4 cents per kilogram
Calcined dolomite	6% ad valorem	30% ad valorem
Kieserite, natural	Free	Free
Epsom salts, natural	3.7% ad valorem	20% ad valorem
Magnesium hydroxide and peroxide	3.1% ad valorem	25% ad valorem
Magnesium chloride	1.5% ad valorem	5% ad valorem
Magnesium sulfate	3.7% ad valorem	20% ad valorem

Because the impetus for making automobiles lightweight is to save fuel, it is important to ensure that a net energy savings is realized over the life cycle 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 a net energy savings by substituting lighter weight materials in automobiles. For example, the Volvo LCP 2000, a concept car that contained several lightweight materials, including ≈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, <60% that of an equivalent-size conventional automobile (Volvo, no date). In addition, new, less-energy-intensive processes for production are being considered, and savings can be further increased significantly by material recycling at the end of the product's life cycle.

1.3 HISTORICAL USE OF MAGNESIUM IN TRANSPORTATION

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. High stiffness and low density, combined with good strength and excellent dent resistance, make Mg alloys particularly valuable for automobile applications. Magnesium has been used successfully over the past 70 years in large numbers of automobile components, most of them die castings. Ford automobiles contained Mg pistons in the 1920s, some Cadillacs and Lincolns contained Mg crankcases, and, in the 1930s, Fords contained Mg oil pans and starter and generator end plates. Other cast Mg parts in automobiles at that time included oil pump housings, engine cooling fans, blower impellers, gear boxes, and headlight brackets. Growth halted during World War II but resumed in earnest after the war. Table 4 lists some of the many Mg automotive applications through 1988.

The outstanding example of Mg's use for automotive castings is the Volkswagen "Beetle." The Beetle used an air-cooled engine with 10 Mg castings, including the crankcase and transmission housing. All but one of the Mg components were pressure die castings (a camshaft gear wheel was made by centrifugal casting). By 1980, the more than 19 million Beetles that were built contained 380,000 metric tons of Mg, i.e., an average of 44 lb per car. Maximum annual use of Mg alloy by Volkswagen, i.e, 42,000 metric tons, occurred in 1971. The use of Mg in automobiles dropped sharply when Beetle production ceased. In 1985, the total use of Mg in cars and trucks manufactured in North America was only 2700 metric tons. Dow and Norsk Hydro made a strong sales and technical development effort during the ensuing years and by 1994, total use was 27,000 metric tons. Current use is estimated at 4.2 lb per car and light truck (Clow 1996) but there is large variation. Some models contain no Mg, whereas others, like the Ford "Windstar" minivan, contain more than 30 lb.

The best example of the use of wrought Mg in road vehicles is in trucks built by Metropolitan Body Company, a subsidiary of International Harvester, during 1955-1965 (Couling 1975). A typical Metro-Lite truck is shown in Figure 2. The body was ≈11 ft long and was a monocoque-type construction that consisted of Mg sheet (0.125 in. thick) and extrusions for upper side panels, floor center panel, side roof rails, rub rails, side door posts, rear door posts, rear door header, and floor cross sills. Aluminum was used for the door and roof panels, whereas fiberglass was used for the front and rear roof caps and front quarter panels. The total amount of Mg in the 1100-lb body was 460 lb. The weight of a corresponding all-steel body was nearly 2000 lb, for a total weight saving of almost 900 lb. The sheet and extrusions used in these vehicles were mill primed with zinc chromate. We believe that the insides of the vehicles did not receive any additional finishing treatment, but the outsides were painted. Over a 10-year period, ≈6300 trucks were produced, and typically used by bakeries. The line was dropped in 1965 when Metropolitan Body was sold.

Advantages claimed for the Mg body were

Greater payload or lower operating costs for equal payload.

Better body dent resistance, when compared with steel.

Table 4. Magnesium applications in vehicles for model years 1921-1988 (Source: Mezoff 1987)

Part	Period	Product Form
Pistons	1921	Castings
Horn discs	1920s	Sheet
Wheel centers for coal mine car	1926	Castings
Truck wheels	1927	Castings
Artillery wheels	1929	Castings
Crankcase, London bus engines	1930	Castings
Oil pumps	1930s	Die castings
Generator mounts and housings	1930s	Die castings
Distributor and magneto housings	1930s	Die castings
Headlight brackets	1930s	Die castings
Fan blades	1930s	Die castings
Camshaft housing and cover	1930s	Castings
Oil filters	1930s	Die castings
Clutch housings	1950s	Castings
Lizenz oil pans (Ford)	1930s	Castings
Transmission housings (Opel)	1930s	Castings
Transmission housings, crankcases (VW)	1933	Castings
Gearcase, armored car control	1940s	Die castings
Farm tractor transmission case	1947	Sand castings
Folding top pillar, steering column shroud and brackets, instrument panel cover, gear shift lever brackets, engine front oil seal plate, oil pump and cover, oil filter body, transmission gear shift rail guide, gear shift housing, clutch housing, fan spacers, distributor housing, carburetor body, window control mechanisms (Chrysler)	1952	Die castings
Delivery truck bodies	1950s	Plate, extrusions
Truck cab components	1950s	Sheet and plate
Blower fan (Chevrolet Corvair)	1950s	Die casting
Automatic transmission stator blades	1950s	Extrusions
Fuel pumps (AC Spark Plug, div GMC)	1950s	Die castings
Dash panel (Chevrolet)	1961	Die casting
Oil pump, gear housing, clutch and transmission housings (VW, Audi, British Leyland, Chrysler)	1960s	Die castings
GTV 2 5-6 parts (Alfa Romeo)	1964	Die castings
Wheels (Fiat)	1967	Die castings
Cylinder head covers, distributor support, oil filter support, oil fume engine breather body, oil pump trumpet oil seal (Fiat)	1967	Die castings
6-cylinder crankcase (Porsche)	1968	Die castings
Differential housing, gearbox cover (Porsche)	1972	Die castings

Table 4. (Cont.)

Part	Period	Product Form
13 × 5.5 in. wheel (Kobe Steel)	1972	Die casting
Solex carburetor (Renault 18 Turbo, Fuego)	1974	Die castings
Motorcycle wheels (Austria)	1975	Die castings
Motorcycle engine parts (Austria)	1975	Die castings
Wheels (Alfa Romeo Spider Veloce)	1978	Low-pressure casting
Manifold vacuum connector (Chrysler)	1976	Die casting
Motorcycle forks (Suzuki 370)	1978	Die castings
Clutch housing, steering column lock housing, brakes and clutch pedal bracket, window regulator stem (Ford Light Truck)	1979	Die castings
Rocker shaft cover (Peugot)	1979	Die casting
Steering column hardware, brake pulley (Volvo)	1980	Die castings
Air cleaner cover (Chevrolet Corvette)	1980s	Die casting
Glove box door	1980s	Die casting
Rocker arm cover (Chevrolet Corvette)	1981	Die castings
Shift handle (Chrysler)	1980s	Die castings
Engine fan, oil pump, cylinder head cover (Mercedes Benz)	1980s	Die castings
Air intake grille, headlight door (Pontiac Fiero, GXC)	1980s	Die castings
Air and vacuum pump brackets, power steering housing, electronic "Delcotron" mounting brackets (Buick GMC)	1982	Die castings
Cylinder head cover (Honda)	1982	Die castings
Valve housings, fan, fan housings, intake manifold (Porsche)	1980s	Die and sand castings
Front-wheel-drive transaxle case (VW)	1980s	Die castings
4-wheel-drive transfer case (Ford)	1985	Die casting
Bulkhead rack for refrigerated vans	1980s	Extrusions
Viscous fan drives	1986	Die casting
Cylinder head cover (Cadillac Allante)	1987	Die casting
Brake and clutch pedal support (GM-10)	1988	Die casting

A lighter chassis could be used because of reduced body weight.

Lower vehicle registration fees.

In 1975, the Dow Chemical Company attempted to determine the service experience of these trucks. They were able to trace 20% of the trucks, and spoke to a representative of each of the eight owner companies. Universally, they reported no corrosion problems or other problems

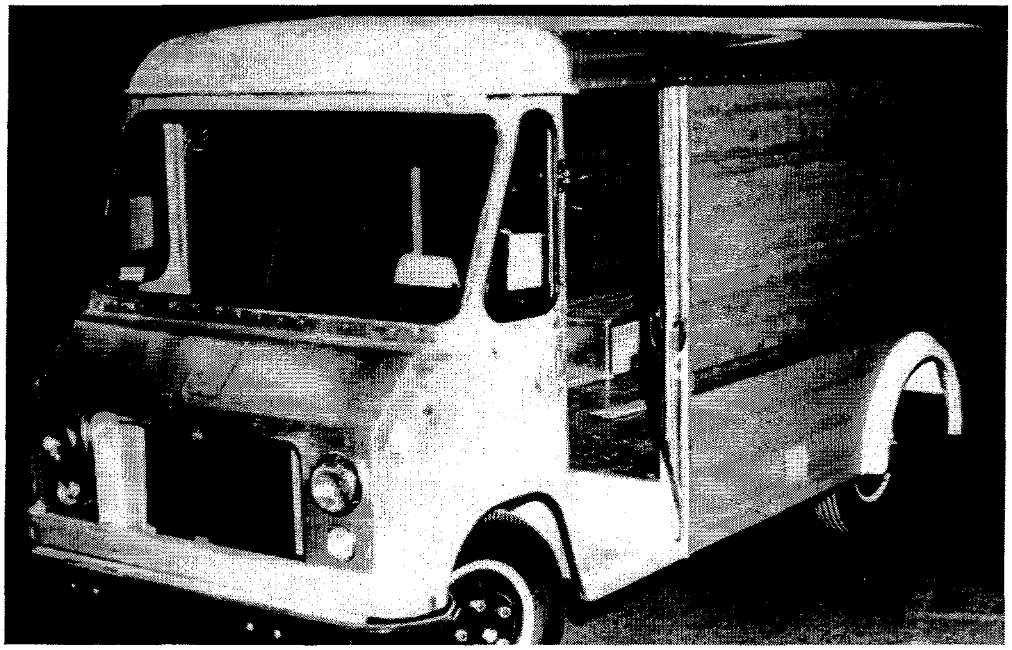


Figure 2. Metro-Lite truck (Source: Couling 1995)

associated with the use of Mg. Favorable comments included better gas mileage, improved tire life, better corrosion resistance than steel trucks, and much easier repair than for Fiberglass.

Although many small castings are currently used by the automotive industry, the use of Mg wrought products is insignificant. Some wrought parts under evaluation are listed in Table 5.

1.4 SCOPE OF THIS STUDY

Our work explores possible 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 use, as well as improvements in fabrication process or design to make the substitution of Mg for other materials technically and economically feasible. We adopt a simple, several-step approach. In Section 2, we define the material requirements for automotive parts by type of part for the three main vehicle systems (body, powertrain, and chassis); in Section 3, we briefly characterize the physical properties of Mg and its alloys; and in Section 4, we describe the processes for production and fabrication. Additional details are provided in Appendixes A and B. Examples provided by the history of Al substitution are examined when appropriate. Finally, in Section 5, we identify potential areas for increased use of wrought Mg in automobiles and the barriers to be overcome before this potential can become reality, and we recommend R&D areas to help remove the barriers.

Table 5. Wrought magnesium alloy parts under evaluation by the automotive industry (Source: Barnes 1994)

Part	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 minispare	Stamped center	AZ31B
	Extruded rim section	AZ61A
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

2 MATERIALS USE IN AUTOMOTIVE COMPONENTS

2.1 MAJOR SYSTEMS OF A PASSENGER CAR

Most auto parts and components are made from relatively few common materials. The simplest approach to the study of the use of Mg in the automobile industry is to look at material use by major system, and then correlate the material with function and/or manufacturing process. The three major component groups of a passenger car are the body, the powertrain, and the chassis. The major systems and subsystems, each made primarily of at most a few types of materials, are summarized in Table 6. The distribution of mass among the major systems is shown in Table 7.

2.1.1 The Body

The body is the largest system (> 40% of the total mass), and it includes the single largest component, the body-in-white (b-i-w), which by itself constitutes ≈25% of the total vehicle mass. Parts included in the b-i-w are shown in Figure 3. 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, an analogy with Al is useful. The fact that both of these metals can be easily extruded gives them a clear advantage over steel (seamless pipe is as close as steel gets to extruded shapes). However, 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. Significant mass reduction is potentially achievable with such a concept, or with a hybrid structure made of some extrusions and some stamped 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 of Mg sheet

Table 6. Components in the three major auto systems

Body	Powertrain	Chassis
Unibody	Engine	Suspension system
Closures	Engine accessories	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
	Transfer case (4-wheel drive)	Wheels and tires
Instruments and controls		
Climate control		

Table 7. Passenger car systems as percent of total mass (Source: ANL estimates)

System	% mass
Body group	
Body-in-white	26
Interior components	10
Glass	3
Other	4
Powertrain group	
Engine	14
Transmission	5
Other	8
Chassis group	
Wheels/tires	6
Brakes	5
Suspension	4
Bumpers	3
Others	8
Fluids	4
Total	100%

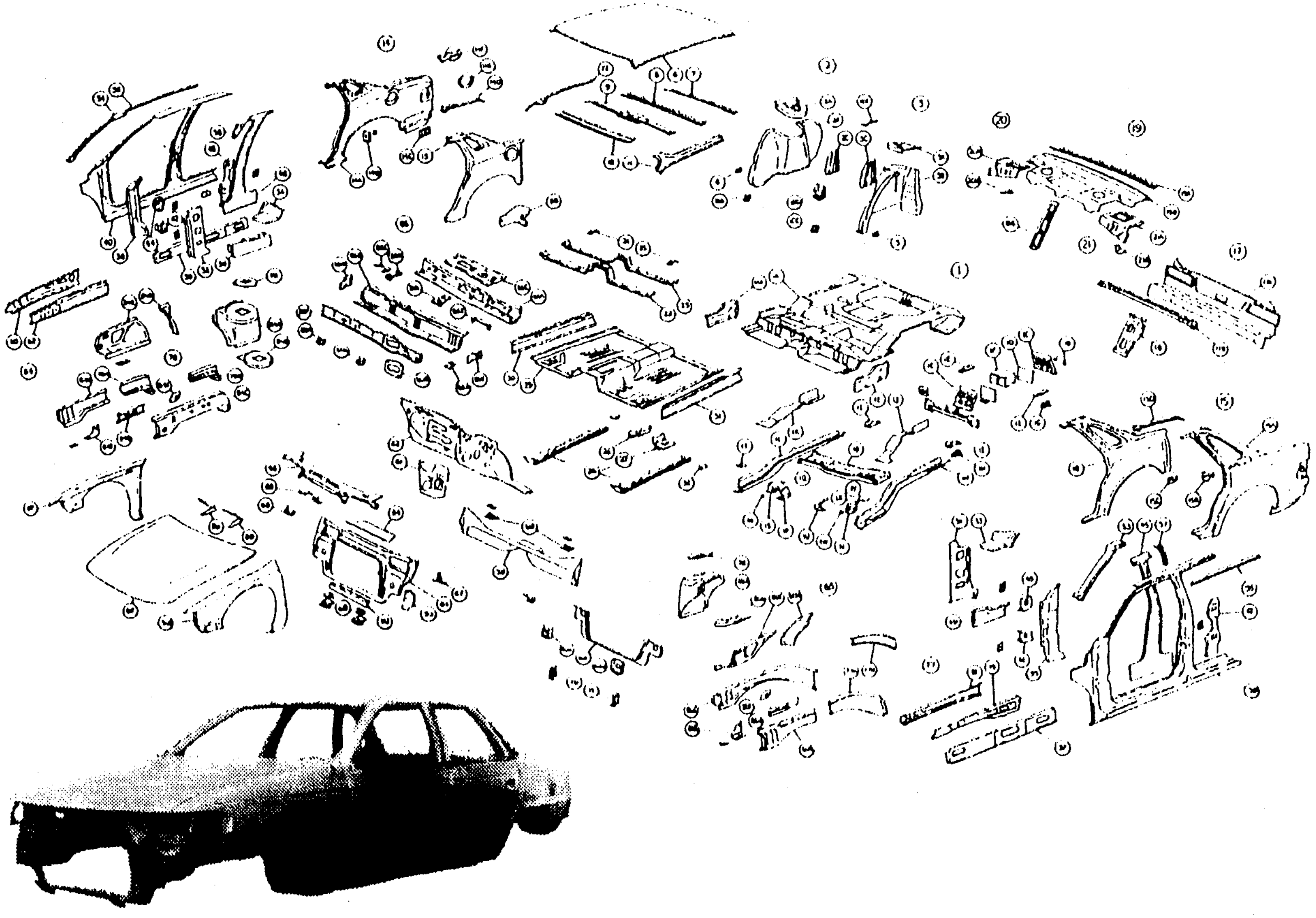


Figure 3. Body-in-white and its various constituent parts (Source: Cornille 1993)

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 deck lids, 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 (when compared with stamping steel). Development of a practical, high-productivity hot-forming process for Mg that requires one or two forming steps to achieve the same result as four hits in a current steel press line would be very attractive, and perhaps justifiable. One precedent for such a development is the hot-stamped side-impact door beam process (980°C) that Ford recently adopted. It turns 50-ksi (yield strength) steel into a 180-200-ksi material, which is a better product, at a lower cost.

The best opportunities for wrought Mg in auto body components lie with the use of extrusions for 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 total Mg use. 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. An extruded Mg seat frame is shown in Figure 4. Such hybrid structures could also be considered for primary body structures. The use of Mg sheet in body panels is technically feasible, but not yet economical. It could be enabled by development of an economical, high-volume, hot-forming process.

The following sections provide additional information on spaceframes for the interested reader. The general reader may wish to proceed to Section 2.1.2.

History of Spaceframes. Spaceframes were developed for racing and sport cars in the early 1950s, as a natural consequence of the search for a lightweight structure with significantly higher torsional rigidity than the simple ladder frames used earlier. Until the mid to late 1930s, racing car chassis were based on the conventional c-section ladder frames then used in most passenger cars. In 1934, however, Porsche introduced an Auto Union racer with a tubular chassis frame. The closed section for the main frame members proved significantly stiffer. In 1937, Mercedes-Benz also used tube frames, this time of oval cross section, to increase rigidity in both torsion and bending. After World War II, the basic tubular ladder frame began to appear with ancillary (tubular) superstructures, which added a somewhat three-dimensional, or "solid" structural characteristic. In 1952, two new chassis appeared that were based on a true "spaceframe" concept: the Lotus Mark VI and the Mercedes-Benz 300SL. The success of these vehicles led to a widespread adoption of this type of chassis frame on most racing and sport cars. The spaceframe concept was partially superseded by the fabricated Al monocoque body (introduced in the Formula 1 circuit in 1963 [Lotus 25]), which has essentially no frame. This type of frameless body still reigns supreme, although a major material change to composite carbon-fiber bodies started in 1981, with the introduction of the McLaren MP 4 Formula 1 racer.

Figure 4. Extruded magnesium seat frame (Source: Courtesy of Findlay Industries)

The main attraction of a spaceframe chassis is that it is relatively inexpensive to make (in small volumes), and provides very high rigidity, in both bending and torsion, with a very low mass. In this respect, spaceframes are second only to monocoque bodies. The monocoque body is more efficient than the spaceframe at providing structural rigidity per unit mass, but it is also more expensive and difficult to make in small volumes.

Applying racing and sport car experience to regular passenger cars, we can make several observations about potential future applications. First, a unibody with load-bearing skin panels is the most efficient structure for a passenger car (provides highest rigidity with the least mass), and, if produced in large volumes by a sheet stamping/weld joining process, it is the most cost effective as well. Therefore, passenger cars produced in large volumes should be made this way, whether the main material chosen is steel or aluminum (joining of aluminum would include bonding). On the other hand, when the volume of production is relatively small (<50,000 units per year), the stamping process becomes very expensive because of its high tooling cost. Specialty cars, such as the Dodge "Viper" or the Chevrolet "Corvette," rely on a spaceframe (tubular for the Viper, mostly stamped for the Corvette), skinned mostly with nonload-bearing polymer sheets. The extruded Corvette rear subframe is shown in Figure 5. Although this approach may not result in significant mass savings, it reduces tooling investment, and thus production cost. An aluminum spaceframe structure is shown in Figure 6. A similar design could be made from Mg, with potential weight savings.

However, if this same basic approach is modified to incorporate lightweight materials, and perhaps a more efficient use (structural) of the skin, it may be possible to achieve significant mass reduction. An Al or Mg spaceframe could possibly save ≈50% of the mass of the equivalent steel frame (a few hundred pounds at present). If (formed) Al or Mg sheet can be used on selected sections of the spaceframe (firewall, floor panels, for example), it would increase the rigidity of the structure

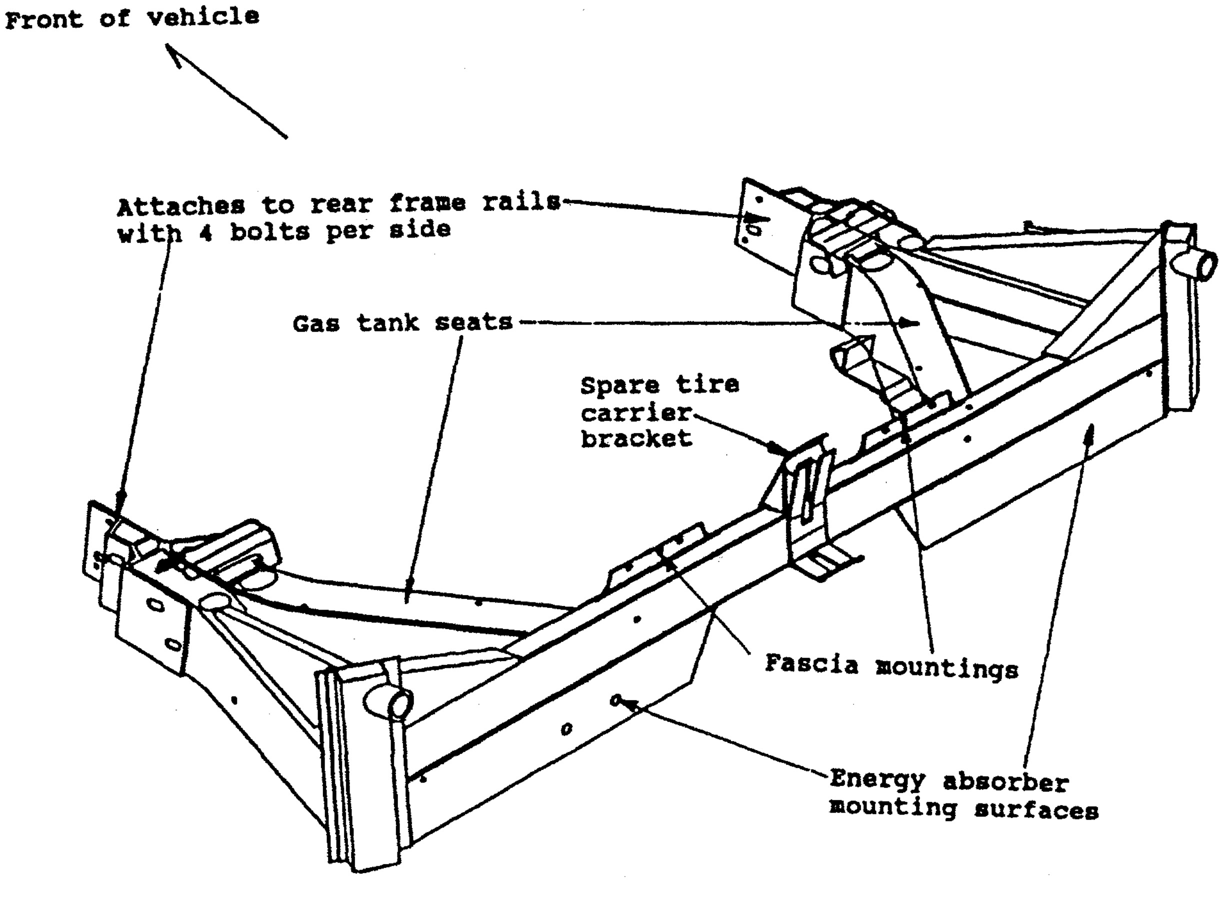


Figure 5. Corvette rear subframe (Source: Matthews 1993)

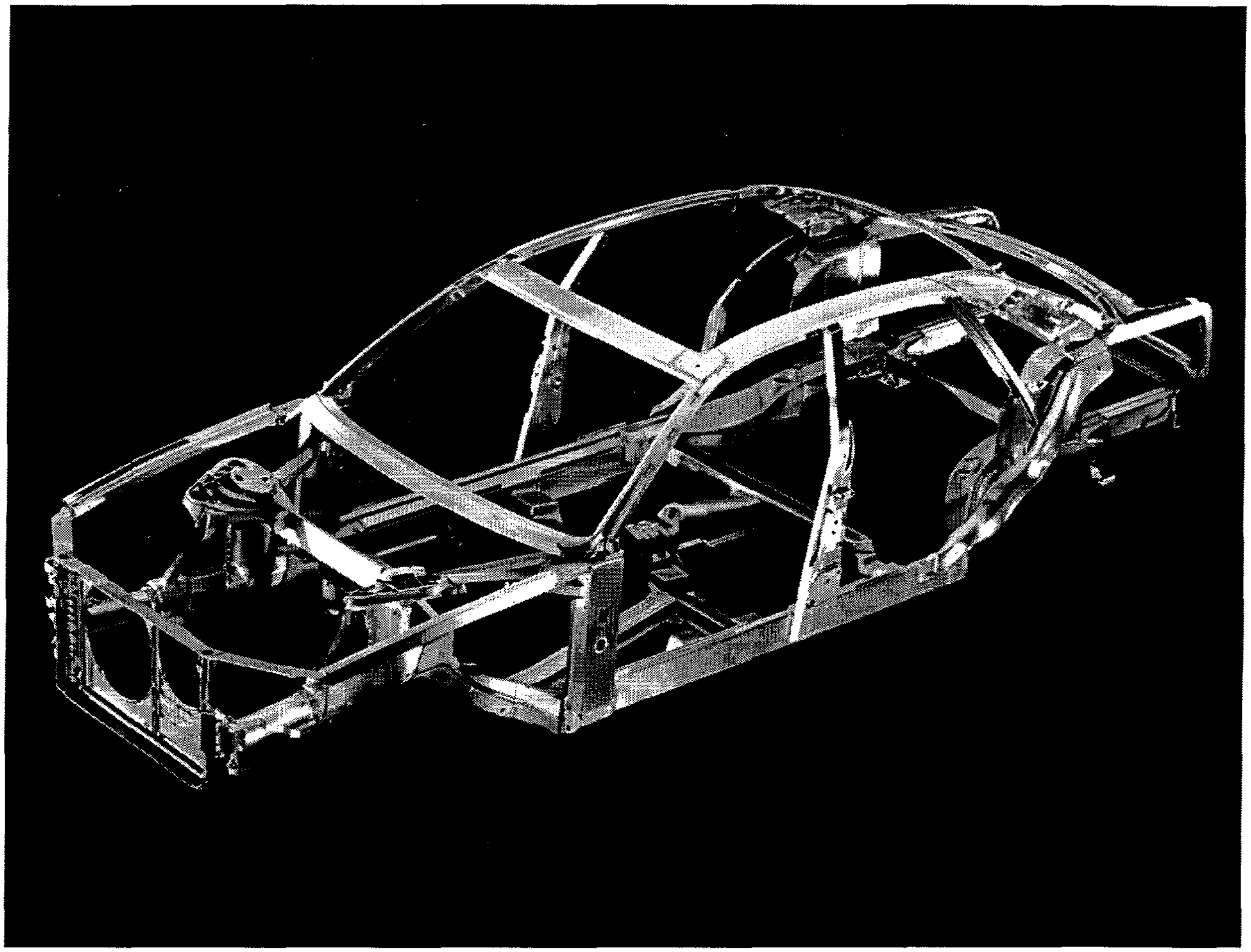


Figure 6. Aluminum spaceframe (Source: Paefgen 1994)

while adding little, if any, to the cost, and still allow design flexibility (only skin panels are replaced during most model changes). Therefore, spaceframes of lightweight materials could find applications in vehicles produced in modest quantities, such as sport or luxury cars, and electric or alternative-fuel vehicles.

Technical Information on Spaceframes. The design of a spaceframe integrates every component into a structural entity, featuring straight and curved extruded sections joined by complex die-cast nodes at key intersections and connection points. The integration of materials, product, and process design with test, evaluation, characterization, and the material properties database plays an important role in the application of Mg spaceframes to the automobile industry. In practical manufacturing, five or six sheet stampings have been consolidated into one complex, high-performance casting. As many as 10-12 parts have been combined into one assembly of two or three extrusions and one casting. Instead of spot welding 300 or more stamped-steel components together to form the car's structure, fewer than 100 extrusions and interconnecting die-cast nodes are robotically welded to form the spaceframe structure.

In spaceframe structures, the extrusions are in areas prone to damage in collisions, particularly as crumple- or crash-management zones for the front end. This application demands tight-tolerance, thin-walled, hollow extrusions that are heat treated for ductile, energy-absorbing behavior and possess the formability necessary for bending into complex shapes. Highly ductile and deformable castings serve as the joints of the structure. They stiffen the spaceframe and act as distribution points for the forces that enter the structure. If Mg spaceframes are to become feasible, alloys sufficiently ductile for these castings must be developed. The extrusions and castings, each optimized to meet individual performance requirements, are then joined together by large-production-volume robotic-welding processes. The net result is a potentially significant weight reduction with an increase in energy-absorbing capability in the spaceframe when compared with today's steel monocoque structures.

A comparative analysis by Alcoa, combined with additional information, including comprehensive structural design and evaluation, showed the design flexibility and weight-savings potential of Al alloys for a spaceframe. Considerations in the analysis, many of which also apply to Mg, include

> The fact that the yield strength of Al sheet and extrusions is equal to or greater than that of comparable sheet steel.
>
> Aluminum's low modulus of elasticity demands changes in product geometry, such as greater wall thickness and changes in cross-sectional area where rigidity is important.
>
> The low density and product stiffness of Al offers greatest weight-saving potential where structural members are subjected to bending stresses, where energy absorption is needed, and wherever dimensioning for strength is possible.
>
> The ability to produce a variety of product forms offers significant advantages by enabling designers to engineer in optimum performance for specific applications, for example,
>
>> Cast and extruded shapes that facilitate geometric and functional integration and part consolidation.
>>
>> Castings, designed for maximum rigidity, that create a potential increase in bending and torsional stiffness.
>>
>> Designing extruded box sections as single members to eliminate the loss of rigidity associated with conventional spot-welded seams.

> The ability to vary wall thickness for increased performance by delivering the material exactly where needed.

Audi and Alcoa reported that the Al spaceframe offers several advantages to car owners, car companies, and, most importantly, the environment. The first advantage is a weight saving of 35% or more over the traditional steel unibody.* This advantage leads to improved fuel economy and reduced emissions without downsizing the vehicle or compromising passenger comfort or safety. Second, the potential for increased stiffness results in improved ride and handling without added weight. Third, tooling expenses and parts inventories are reduced, and manufacturing and design-to-production schedules are more efficient. Another advantage is economical and improved recyclability.

Aluminum spaceframes offer a 35% weight savings over steel body structures, and it is expected that more weight reduction can be achieved by Mg spaceframes, provided energy absorption capability, strength and ductility, specific stiffness, corrosion, and fatigue resistance of the Mg alloys can be made competitive with those of Al and steel through proper design. The availability of appropriate alloys, and high-volume, cost-effective manufacturing techniques for using them, such as thin-wall extrusion, vacuum die casting, precision bending, and high-efficiency joining processes, are the keys to the Mg spaceframe structure.

Spaceframe R&D. The analysis and evaluation of Al alloys for spaceframes can be applied to Mg alloys as well. In general, several questions about Mg alloys should be clearly defined and answered by a research program:

> Are the strength properties of Mg sheet and extrusions equal or comparable to those of Al? What is the crush behavior of extruded Mg rails?
>
> Can the drawback of Mg's low modulus of elasticity be overcome through structural design (increased wall thickness, reinforced supporters) with minimum weight penalty?
>
> Do the Mg extrusions and castings exhibit enough energy absorption capability (good strength and high ductility) for crash management? Can more ductile alloys be developed?
>
> Can Mg alloys be fabricated into a variety of product forms cost effectively, and are the advanced techniques for manufacturing Mg alloys, such as extrusion

---

*This can be compared with the 48% savings achieved by using Al sheet for the b-i-w of a Mercury Sable.

bending, vacuum die casting, thin-wall precision extrusion, and high-quality, high-rate joining, available and mature enough for use by the industry?

Is the corrosion, fatigue, and creep resistance database for Mg alloys in various product forms available for the engineering design?

Is there a need for scrap separation processes to separate cast from wrought Mg alloys and to separate alloys within families?

What is the weight-saving potential for an Mg spaceframe? How could costs and weight savings be optimized by using a hybrid stamped/extruded structure?

To answer these questions, systematic analysis and experiments should be carried out in close cooperation with the auto industry, Mg manufacturers or producers who have expertise in the area of material data and characterization capabilities, and government laboratories or universities that can contribute to theoretical understanding and simulation.

From the manufacturing and/or metallurgical standpoint, R&D should be concentrated on development of appropriate alloys, and on the techniques for using them best (vacuum die casting, extruding, part forming, and microstructural modification). In the die casting arena, die treatment, materials of construction, surface treatment and lubrication, and controlled filling and solidification (porosity volume and distribution) of Mg alloys represent the important areas of focus. The vertical vacuum casting process shows potential for use with Mg as a spaceframe structural material for the high-quality casting nodes. Extrusion produces tight-tolerance, thin-walled, hollow parts with high ductility and the capacity for stretch forming or rotary-draw bending.

Grain structure plays an important role in the quality of the Mg extrusions. For example, a small-grain structure improves extrudability by reducing the pressure required for extrusion, and allowing increased speed. Furthermore, a small grain size implies a large grain boundary area and easy sliding and rotation of adjacent grains, thus decreasing strain constraints. Consequently the residual stresses after extrusion may be diminished, and distortion of large dimensional sections may decrease. Therefore, the technique to produce a structure with a fine, uniform grain for large extrusions is important not only for better extrudability and product quality but for the high strength and ductility that are required for the spaceframe's crashworthiness. Improved process control and monitoring techniques, as well as new thermal treatment, quenching systems, and aging practices, would all be useful.

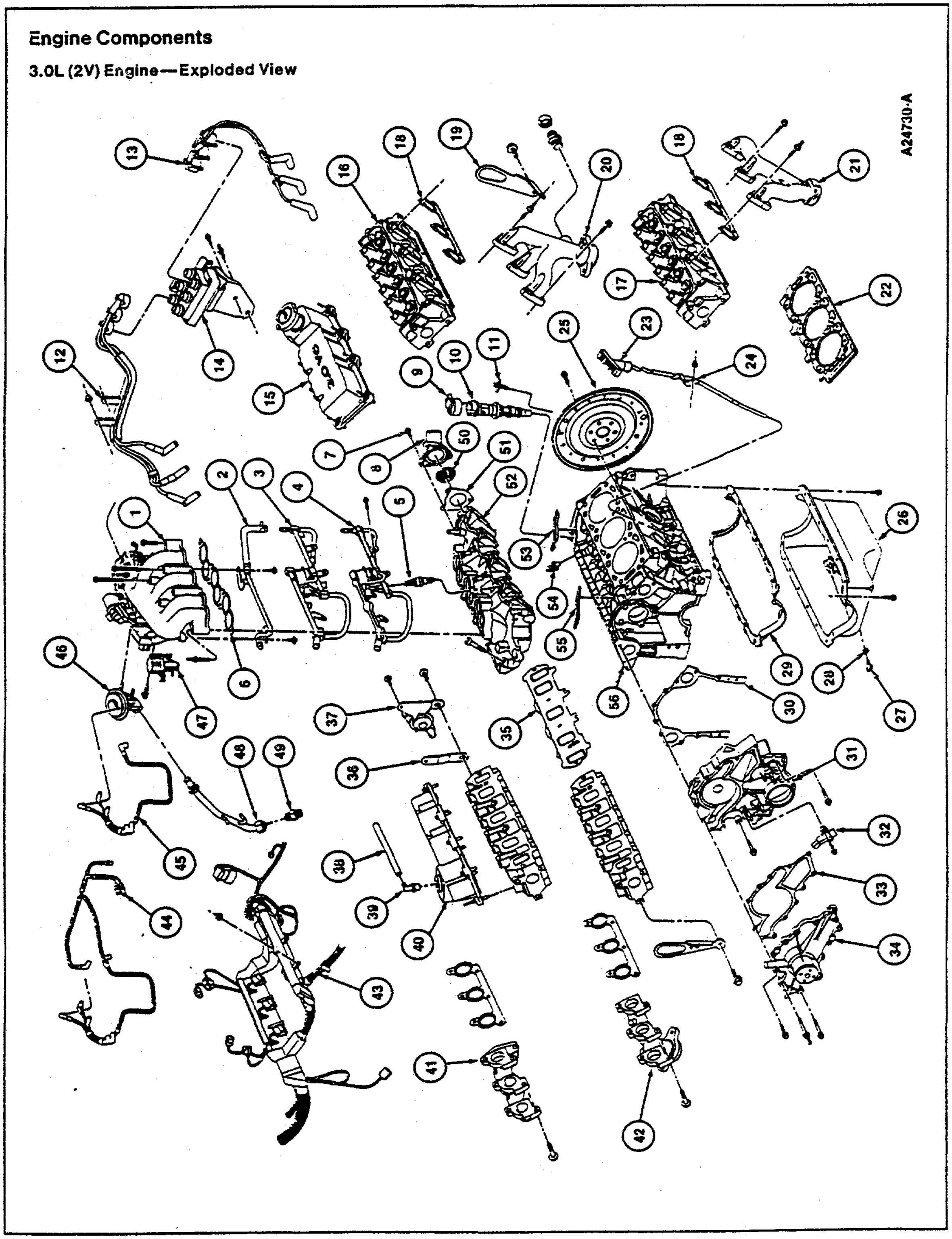
The manufacturing demands of the spaceframe involve five areas: joining, surface treatment, dimensional accuracy and tolerances, speed, and cost. Development of a cost-effective and volume-productive welding process for joining castings and extrusions is needed. The design of joining geometry, the quality of the joint (strength, ductility, fatigue life, and corrosion resistance), and distortion allowance would ensure the integrity and performance of the Mg spaceframe structure. Another important concern is scaling up laboratory-scale processes to volume production rates. The mathematical models and simulations of complex sheet and extrusion forming, extruding, and casting processes that link material descriptions with product design and process analyses are also important for the development of the Mg spaceframe.

> In sheet forming, plastic anisotropy and crystallographic texture orientation during plastic deformation could be simulated to help predict mechanical behavior.
>
> For extrusions, simulation of forming processes, such as stretch and rotary-draw bending, and evaluation of tool and die designs and theoretical models to analyze friction, pre- and poststretching, die contours and springback would enable rapid analysis of changes in extrusion parameters.
>
> Development of ductile alloys for vacuum die casting would be an important technical development for the spaceframe. Simulations of die filling, defect generation, solidification, and thermal management would enable effective process design.

2.1.2 The Powertrain

The components in the powertrain are markedly different from those of the body. The engine and transmission, which constitute the main mechanical groupings in the vehicle, are characterized by complex assemblies of many individual components (see Figures 7a and b for examples of engine and transaxle 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 Fe (older practice). Stressed mechanical components (gears, shafts, etc.) are made from steel bar or forgings, and occasionally from highly engineered stampings or high-grade Fe castings (nodular Fe, etc.). Covers are made from steel stampings, cast Al or Mg, and molded plastics. Such highly specialized components as engine valves, pistons, transmission clutches, bearings, etc. are often made from a combination of materials, by highly developed, unique processes. For example, engine valves are often made from three separate materials welded together (high-temperature-resistance [Ni] alloy for the head, C 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


Engine Components

3.0L (2V) Engine—Exploded View

Figure 7a. Typical components of a current automotive engine (Source: Ford Motor Co.)

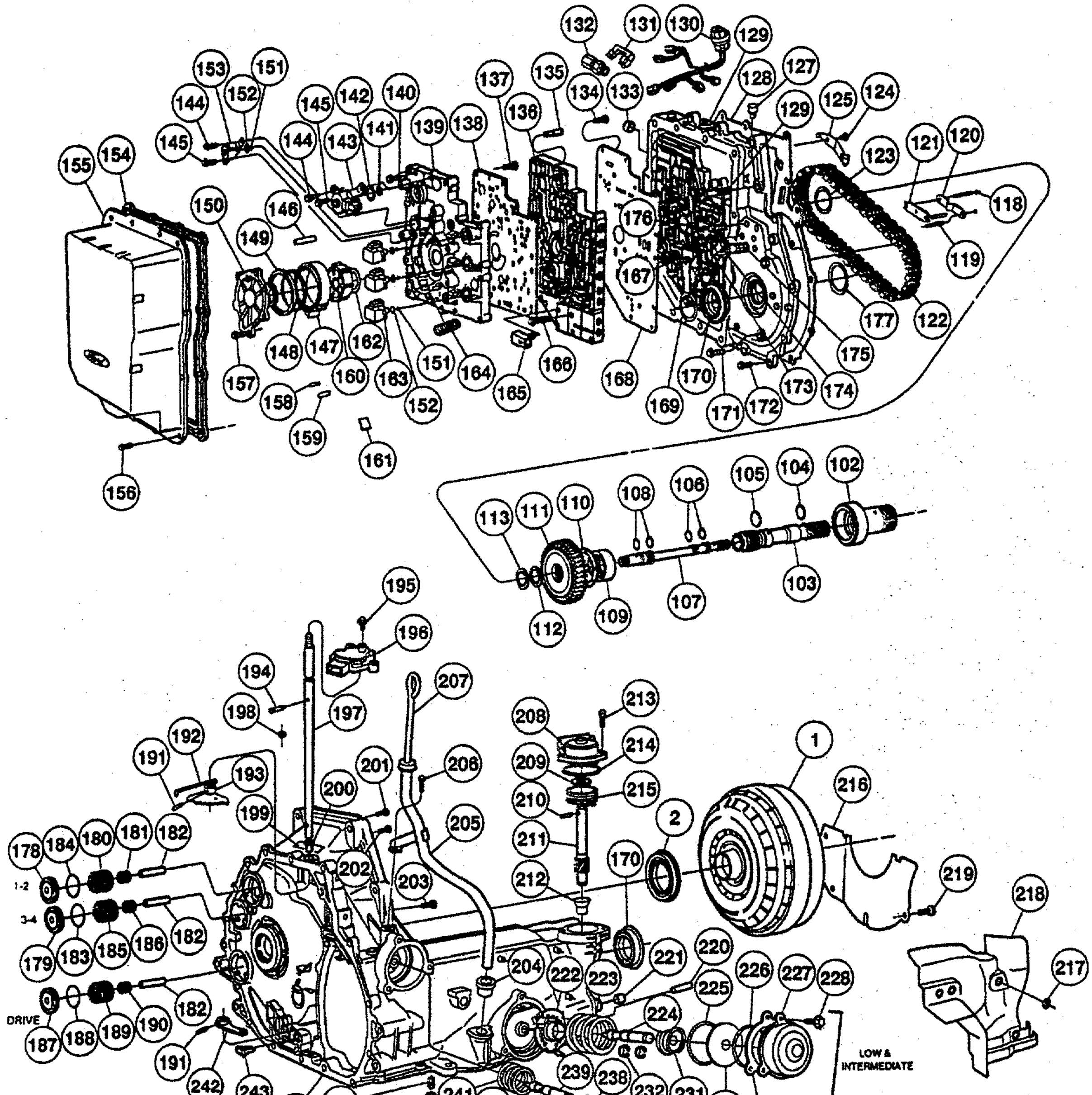


Figure 7b. Typical components of a current automotive transaxle (Source: Ford Motor Co.)

from bar stock or from a near-net form made by casting, forging, stamping, and sintering. Machining, usually fully automatic and often highly precise, includes extensive grinding and even honing.

Trends in material substitution in this group include an essentially universal replacement of cast Fe housings by Al castings, some Mg castings, and, more recently, even plastic moldings; replacement of cast Fe (high-temperature alloy) exhaust manifolds with stainless steel (tube) fabrications; replacement of cast Fe 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 turbocharger 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 example, intake manifolds formerly made from cast Fe, 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 Fe and even Al castings in some housings and covers. However, Mg does not have the same creep resistance as 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 an Mg crankcase, the engine was air-cooled, and the hot components (i.e., the cylinders) were made of cast Fe.* 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.

2.1.3 The Chassis

The chassis components are highly diverse, but their characteristics lie 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

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*Cylinder heads were Al alloy.

with significant structural function, such as the suspension and subframes, are dominated by steel, whereas those with predominantly mechanical functions, such as the steering and brake systems, include more diverse and specialized materials. Examples of these systems are shown in Figures 8 and 9. 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 briefly. 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 in the steering and brake systems are made mostly from cast Al, but some cast Fe still remains. Mechanical components in the steering rack, shocks, and some brake subsystems are mostly machined from steel. Components with intricate geometry, like wheel hubs and steering knuckles, are usually made from cast Fe or, more recently, from cast Al. The exhaust system is made from steel, but the need to endure high temperature and corrosion has dictated several coatings and protective processes and, in some cases, the use of stainless steel. Fuel-storage systems rely on two materials: Sn-coated steel (terne plate) and blow-molded plastics.

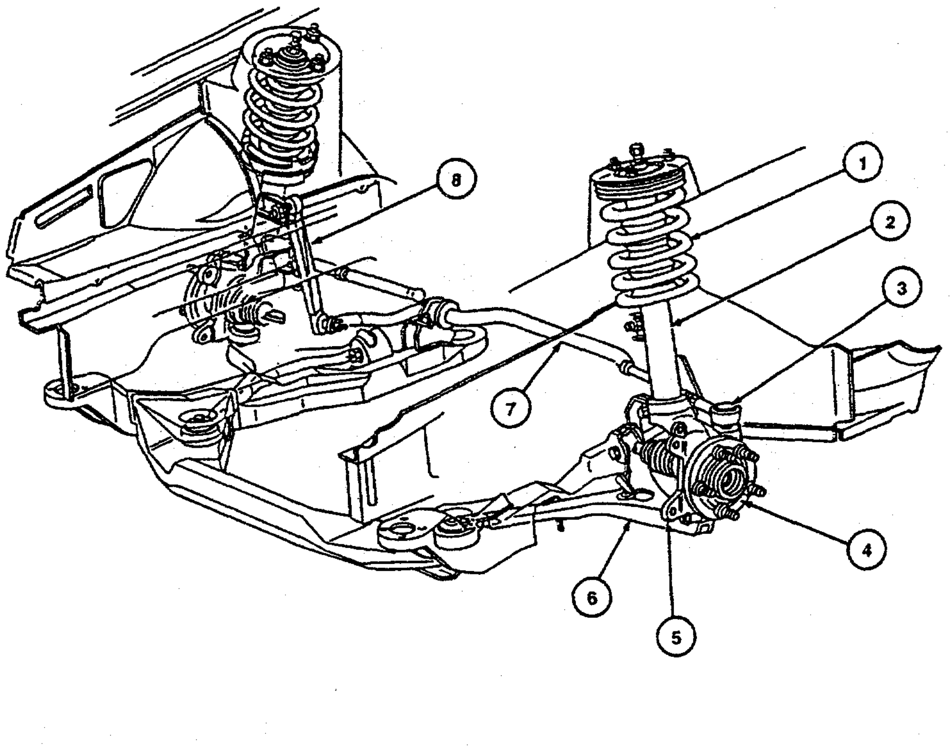

Figure 8. Typical front-wheel-drive front axle and steering components (Source: Ford Motor Co.)

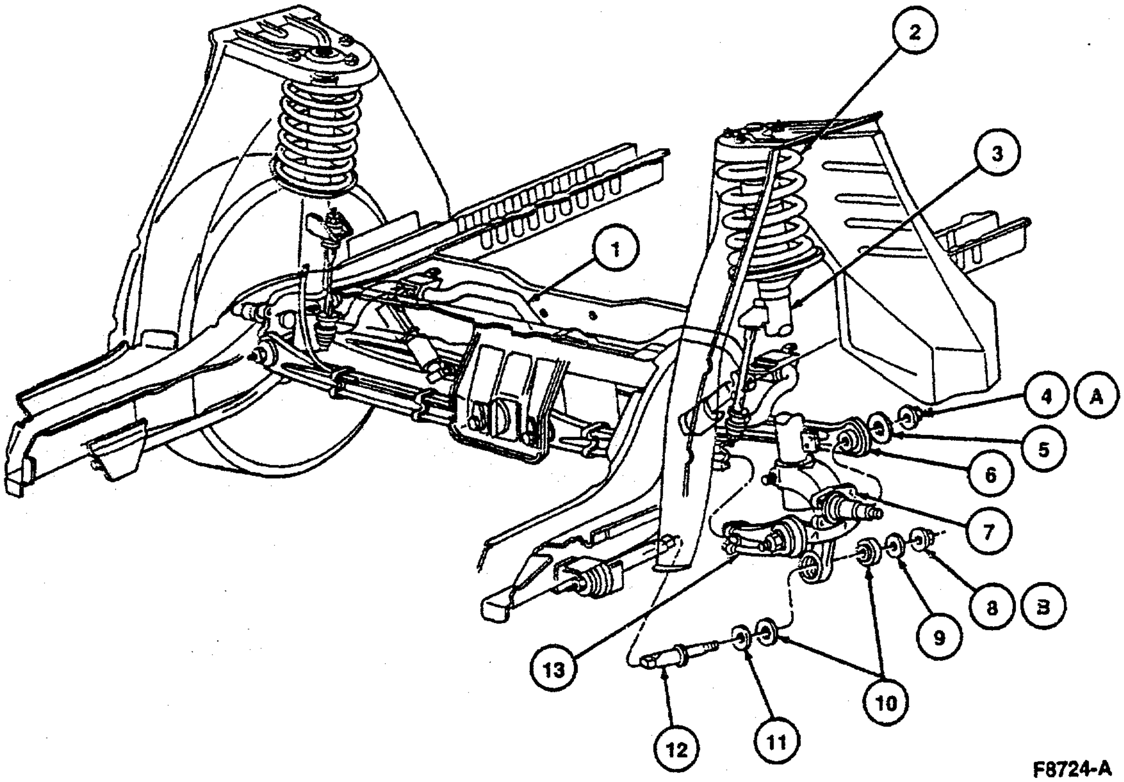

Figure 9. Typical front-wheel-drive rear axle and suspension (Source: Ford Motor Co.)

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 an extruded-Al glass-reinforced composite or from stamped steel. Foundation brake components are still predominantly made from cast Fe, 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.

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.

2.2 MATERIAL COMPETITION AND SELECTION

The material that yields the lowest finished-part cost is generally selected for automotive applications, which 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 for mass-market vehicles. 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 in Audi, Ford, and other Al-intensive vehicles.

This study speculates on future automotive applications for Mg, particularly in wrought form. Currently, practically all of the 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. In these parts, Mg has gained acceptance over Al (which had already displaced cast Fe and other alternatives) primarily because it provides a further 30-35% mass reduction with very little additional cost. Actual mass savings depend on the type of part; Mg's lower modulus may necessitate a thicker part and reduce savings. Magnesium die castings are very competitive with Al castings, not only because they require less mass, but also because the lower solubility of Fe and lower heat capacity of Mg enable longer die life and lead 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 uses for wrought Al have been the sheet and tubes 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, decklids, bumpers, and other components were made of wrought Al, sometimes with essentially the tooling designed for steel, when rapid weight reductions were required. However, as soon as less expensive means (mostly with Al castings*) were devised to achieve the same mass reduction, these costly applications reverted back to steel. Now that the most cost-effective mass reductions have been achieved (mostly by replacement of steel with 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 when the material is hot (230-350°C), generally making wrought Mg noncompetitive with steel (or even Al, which can be formed at lower temperatures with existing equipment). 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. Until economics and forming technology are improved, wrought Mg is unlikely to be used as a major material.

However, improvements could result in considerable potential for wrought Mg as an automotive material. With a density 35% lower than that of Al and comparable tensile strength, Mg could be competitive in many applications. Although the cost of the basic material is currently somewhat higher than that of Al, the primary production processes for the two materials are very similar, and there is no clear economic and/or technical reason why Mg must be more expensive. Energy required for Mg production is somewhat higher on a weight basis, but it is lower on a volume basis. 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 earlier state of development of the Mg industry. In addition, new production processes and economical hot forming could reduce Mg material and processing costs. Therefore, it is possible that Mg could become price competitive with Al, even on a per-pound basis, in which case it could experience a dramatic increase in automotive use.

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*Aluminum castings, at four or five times the cost per pound, are quite competitive with the Fe castings they normally replace, because they result in almost 2/3 mass savings. The mass reduction makes the raw castings only ≈70% more expensive (than Fe castings), and because they are also easier to machine, the actual cost of the finished parts is only 50% or less above that of the Fe part, a relatively low premium to pay for a mass reduction of >60%.

3 PROPERTIES OF MAGNESIUM AND ITS ALLOYS

Magnesium is readily available commercially at purities >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, Ce, and Zr, among others The alloying elements Ag and Th are occasionally used in some exotic alloys, and Li has been investigated as an alloying element. This section briefly describes the mechanical properties, corrosion resistance, flammability, and crashworthiness of Mg and its alloys; additional detail can be found in Appendix A.

3.1 MECHANICAL PROPERTIES

The yield and tensile strengths of commercial Mg alloys are comparable to those of Al alloys and can approach those of low-C 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-C 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 significantly less than that in tension. The yield and tensile strength of Mg alloys decreases 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 strength up to 250-350°C.

The fatigue strength of Mg alloys, as determined with laboratory test samples, covers a relatively wide scatter band, with most alloys exhibiting an endurance limit at 10^7-10^8 cycles. The fatigue strength is 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 similar to that of Fe castings currently used as structural parts in automobiles.

Magnesium alloys are sufficiently hard for all structural applications except those that involve severe abrasion. Although rather wide variations in hardness are observed, the resistance of the alloys to abrasion varies by only ≈15-20%. Several Mg sheet alloys exhibit a very high resistance to denting. This characteristic is particularly advantageous for auto parts like doors and hoods.

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 most environments, and the corrosion rate of Mg typically lies between that of Al and mild steel. The corrosion resistance of a part depends upon the environmental conditions, its chemical composition, its history, and its surface condition. For instance, chlorides in marine environments and SO_2 in industrial environments can disrupt the coating and allow severe corrosion. Galvanic corrosion associated with contact with dissimilar metals is a concern, but, in general, Mg alloys are sufficiently corrosion resistant 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 treatment.

3.3 FLAMMABILITY OF MAGNESIUM

Combustion of Mg requires that the metal be hot enough to produce sufficient vapor to support combustion; this occurs at or above the melting temperature of $\approx 650\,^\circ C$. Because the thermal conductivity of Mg is high, an entire massive piece must be raised to very near its melting point and maintained there for it to burn freely. Therefore, auto parts would be unlikely to burn. 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. Special care in machining is, therefore, required (see Sections A.4 and B.4 of Appendixes A and B for more information).

3.4 CRASHWORTHINESS OF MAGNESIUM 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. During collision, the main function of the structural components in these zones is to provide maximum 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, be made of materials that exhibit high ductility and low tendency to fracture at low strains (<30-40%). Materials with poor ductility could exhibit fracture or material separation and thus lead to poor energy management. Therefore, development of high-ductility Mg alloys would be useful.

The passenger compartment must exhibit high structural integrity, especially during side and rollover (roof crash) collisions. The crush characteristics of the load-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.

Because the specific strength of Mg alloys is higher than that of Al alloys and steels, Mg extrusions exhibit greater potential for weight reduction. Because of Mg's low density (and high specific strength), a thick Mg rail that possesses the same crush-loading capacity as a steel rail can be made 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 of the same geometry.

Many automotive components are made from sheet components that are spot welded together at flanges. The elements between the spot welds may separate when subjected to a crush load; adhesive material is sometimes added to overcome this problem. Another alternative, not possible for steel, is to use extruded rails instead of ones that are joined by welding. This option could provide an advantage in terms of crashworthiness for designs that use alloys of either Mg or Al. Crush behavior of extruded Mg rails is an area that should be addressed by R&D; more detail on this topic is provided in Section A.5 of Appendix A. However, it appears that suitably crashworthy designs should be possible with Mg.

4 MAGNESIUM PRODUCTION

4.1 PRODUCTION OF MAGNESIUM INGOTS

Magnesium is the eighth most abundant element in the earth's crust, but never occurs naturally in the uncombined state. Magnesium compounds occur both as solid deposits and in solution in surface waters of the earth. The two most common minerals are carbonates: dolomite ($MgCO_3 \cdot CaCO_3$) and magnesite ($MgCO_3$). The oxide mineral brucite ($MgO \cdot H_2O$) is somewhat less common. Concentrated aqueous solutions in the form of brine deposits occur at several places in the world, but by far the largest deposit is in the oceans of the world. The Mg content of the ocean is 0.13%, which is a lower concentration than the lowest grade deposit of minerals mentioned above (Shigley 1951). However, the ocean represents a virtually unlimited supply, and the uniformity of the Mg content permits the use of highly standardized procedures for its extraction. Seawater is now the main source of Mg. This is a strategic advantage over Al, which is produced from bauxite, which must be imported.

Although many processes have been developed to produce metallic Mg, only three methods are now used. The oldest of these methods, which accounts for 70-80% of present output, involves the electrolytic reduction of $MgCl_2$. The second method is known as the Pidgeon process (Pidgeon 1986), in which dolomite is directly reduced by ferrosilicon at high temperatures in the solid state. It is economical only under comparatively rare conditions in which a natural site advantage exists. The third method is the Magnetherme process (Ball 1955), a more recent nonelectrolytic method developed in France. It is carried out at much higher temperatures with the reactants in the liquid state.

The two largest producers of Mg in the world, the Dow Chemical Company and Norsk Hydro, use electrolytic processes that differ mainly in the degree of hydration of the $MgCl_2$ and the cell characteristics (Pidgeon 1986 and Clow 1992). The first electrolytic process was pioneered by the German firm IG Farbenindustrie early in the 20th century and is now used by Norsk Hydro, which is the main European producer. The second electrolytic process was developed by the Dow Chemical Company and is used at the world's largest Mg plant at Freeport, Texas, where $MgCl_2$ is extracted from seawater. A schematic diagram of the Dow process is shown in Figure 10. In contrast to the IG–Norsk Hydro process, the Dow cells require external heat, with a steel-containing pot serving as the cathode. Cell current is $\approx$60,000 A, which is more than double that normally used in the other process. The total energy consumed per kg of Mg by either of the two electrolytic processes is $\approx$17.5 kWh (8 kWh/lb or 167×10^6 Btu/ton). Norsk Hydro reported an energy consumption for reduction of 5.5-6.4 kWh/lb in 1994, which was a 40% decrease from 1980 consumption (Fougner 1996), and compares favorably with typical Al reduction energy.

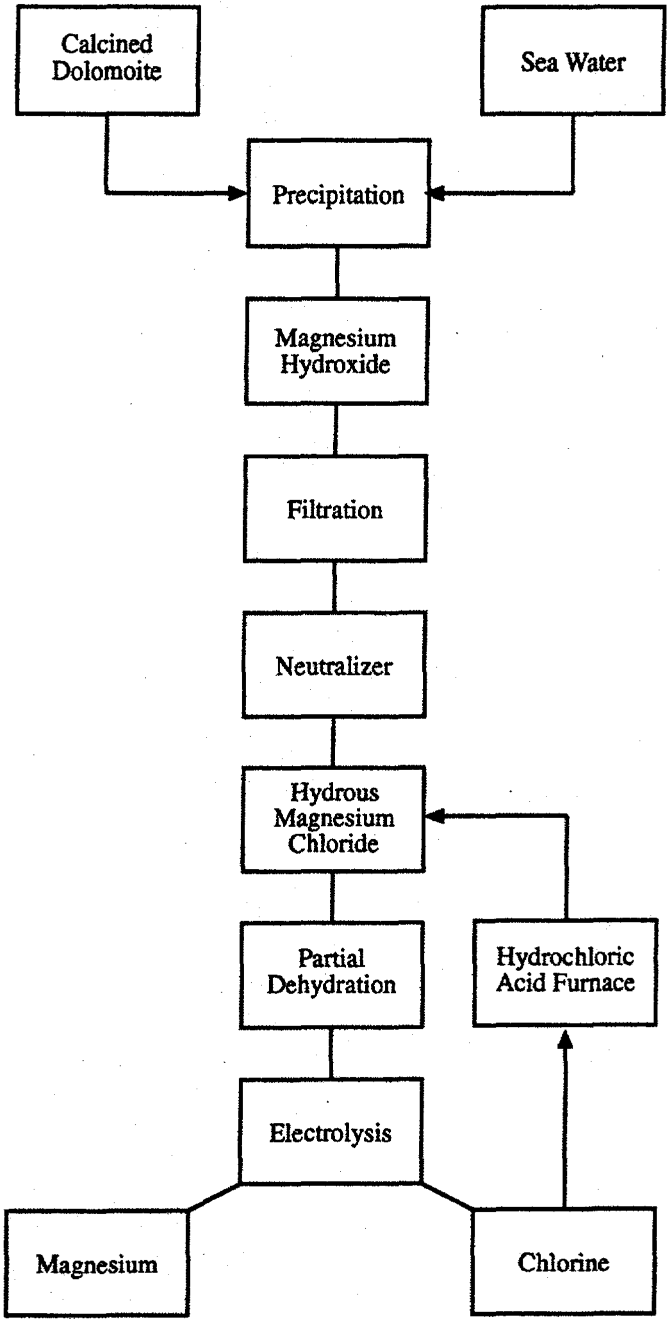

Figure 10. The Dow process of producing magnesium (Source: IMA 1993)

A potentially more economical method to electrolytically produce Mg with MgO 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). This process avoids the high cost of preparing the $MgCl_2$ feedstock, and the losses associated with sludge formation during electrolysis. Actual data from process operation would be required to confirm the promise of this method. Development of this or another innovative process could potentially reduce the cost of Mg as a raw material and greatly improve its competitive position.

4.2 ALLOYING BEHAVIOR

4.2.1 Early Alloys

The earliest commercial alloying elements were Al, Zn, and Mn, and Mg-Al-Zn castings were used extensively in Germany during the World War I. These alloys suffered from corrosion in wet or moist environments, a problem that was overcome by the discovery in 1925 that small additions (0.2%) of Mn increased corrosion resistance (Beck 1940). Alloys based on the Mg-Al-Zn system have remained the principal materials for Mg casting alloys for use at ambient temperatures. The earliest wrought alloy, which contained 1.5% Mn, was used for sheet, extrusions, and forgings, but this material has now been superseded.

In the period between the two world wars, difficulties were encountered with Mg alloy castings because of a tendency toward large and variable grain size that often resulted in poor mechanical properties, microporosity, and excessive directionality of properties in wrought components. In particular, yield strength values tended to be consistently low relative to tensile strength. In 1937, Sauerwald of IG Farbenindustrie in Germany (Beck 1940) discovered that Zr had an intense grain-refining effect on Mg. Paradoxically, Zr could not be used in the existing commercial alloys because it was removed from solution due to the formation of stable compounds with both Al and Mn. This led to the evolution of a completely new series of cast and wrought Zr-containing alloys that exhibited improved mechanical properties at both room and elevated temperatures (Table 8). The alloying behavior of Mg is discussed in more detail in Appendix A.

4.2.2 Metal Matrix Composites

Metal matrix composites (MMCs) offer the potential for tailored mechanical, physical, and thermal properties, and Mg MMCs exhibit greater weight-reduction potential than do Al and Ti

Table 8. Composition (%) and typical room-temperature mechanical properties of magnesium alloys (Source: ASM 1979)

Alloy	Product type[a]	Al	Mn	Th	Zn	Zr	Other	Tensile Strength ksi	Yield Strength (T) ksi[b]	Yield Strength (C) ksi[c]	Elongation in 2 in. %
AM100A-T61	SC/PC	10.0	0.1	–	–	–	–	40	22	22	1
AZ63A-T6	SC/PC	6.0	0.15	–	3.0	–	–	40	19	19	5
AZ81A-T4	SC/PC	7.6	0.13	–	0.7	–	–	40	12	12	15
AZ91C-T6	SC/PC	8.7	0.13	–	0.7	–	–	40	21	21	6
AZ92A-T6	SC/PC	9.0	0.10	–	2.0	–	–	40	22	22	3
EZ33A-T5	SC/PC	–	–	–	2.7	0.6	3.3 RE	23	16	16	2
HK31A-T6	SC/PC	–	–	3.3	–	0.7	–	32	15	15	8
HZ32A-T5	SC/PC	–	–	3.3	–	0.7	–	27	13	13	4
QE22A-T6	SC/PC	–	–	–	–	0.7	2.5 Ag	38	28	28	3
EZ41A-T5	SC/PC	–	–	–	4.2	0.7	1.2 RE	30	20	20	3.5
EZ63A-T6	SC/PC	–	–	–	5.8	0.7	2.6 RE	44	28	28	10
ZH62A-T5	SC/PC	–	–	1.8	5.7	0.7	–	35	25	25	4
ZK51A-T5	SC/PC	–	–	–	4.6	0.7	–	30	24	24	3.5
ZK61A-T5	SC/PC	–	–	–	6.0	0.7	–	45	27	27	–
ZK61A-T6	SC/PC	–	–	–	6.0	0.7	–	45	28	28	10
AM60A-F	DC	6.0	0.13	–	–	–	–	30	17	17	6
AS21A-F	DC	2.0	0.35	–	–	–	1.0 Si	30	19	19	5
AS41A-F	DC	4.3	0.35	–	–	–	1.0 Si	32	22	22	4
AZ91A,B-F	DC	9.0	0.13	–	0.7	–	–	33	22	24	3
AZ10A-F	Ex	1.2	0.2	–	0.4	–	–	35	21	10	10
AZ31B,C-F	Ex/Fg	3.0	–	–	1.0	–	–	38	29	14	15
AZ61A-F	Ex/Fg	6.5	–	–	1.0	–	–	45	33	19	16
AZ80A-T5	Ex/Fg	8.5	–	–	0.5	–	–	55	40	35	7
HM31A-F	Ex	–	1.2	3.0	–	–	–	42	33	27	10
M1A-F	Ex/Fg	–	1.2	–	–	–	–	37	26	12	12
ZK40A-T5	Ex	–	–	–	4.0	0.45	–	43	37	20	4
ZK60A-T5	Ex/Fg	–	–	–	5.5	0.45	–	53	44	36	11
AZ31B-H24	S/P	3.0	–	–	1.0	–	–	42	32	26	15
HK31A-H24	S/P	–	–	3.0	–	0.6	–	33	29	23	9
HM21A-T8	S/P, Fg		0.6	2.0	–	–	–	34	25	19	11

[a] Ex-extrusion, Fg-forging, S/P-sheet and plate, RE-rare earth, DC-die cast, SC-sand cast, PC-permanent cast.

[b] (T) = Yield strength in tension.

[c] (C) = Yield strength in compression.

MMCs. However, because the physical/chemical and mechanical behavior of Mg alloys is perceived as inferior, 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, and engine blocks. This work offers considerable potential for automotive applications.

Mg MMCs are still in the research stage. Attention should still be focused on the relationship between properties and microstructure, the relationship between fabrication processing control and microstructure, and on failure modes that can occur in Mg MMCs. Mg is very reactive in the molten state; the effects of chemical reactions between the matrix and the reinforcements at the interfacial structures on mechanical and physical properties of the composites may be different from those of other MMCs. The reaction mechanisms and kinetics of the matrix and reinforcements, and control of the reaction through fabrication parameters, are important keys to production of reliable MMC components.

Currently available fabrication processes for Mg MMC components include squeeze casting, semisolid casting (rheocasting, thixocasting, and compocasting), extrusion processes (powder and billet), sinter forging, and powder metallurgy techniques. Problems that have been encountered in these processes are distribution of reinforcement within the matrix (particulate segregation and agglomeration), degradation of the mechanical properties due to reactions at the matrix/reinforcement interfaces, poor wetting and bonding between the matrix and reinforcements, entrapment of gas and porosity inside the MMCs, heat transfer management during the solidification process (the ceramic reinforcement acts as a heat sink during the heating and cooling process, which makes the heat transfer of the whole system more complicated than for a simple alloy system), corrosion of the MMCs, slow processing rate, and high cost. Although some of the problems, such as the distribution of the reinforcement, have been solved by commercial companies and large-scale batches can be produced uniformly, other problems still exist, and the optimized processing route for various reinforcement systems and a database of mechanical/physical properties are not yet established.

An additional technical deficiency that limits widespread application of MMCs is a lack of data on properties such as fatigue, creep, wear, and corrosion. Hence, establishment of a secondary-properties database for Mg MMCs is also important. Furthermore, technological challenges that must be met include development of a rapid and inexpensive machining process, near-net-shape forming technology, techniques for joining MMCs to other materials, and the development of recycling processes. If these challenges are met, use of Mg MMCs could enable significant weight reduction in automobiles.

4.3 FABRICATION OF PRIMARY SHAPES

Section B.3 of Appendix B contains detailed information on fabrication; highlights are summarized here. Sand and permanent-mold castings can be used to fabricate, from Mg alloys, extremely intricate shapes with mechanical properties, castability, and resistance to microshrinkage that are competitive with those of castings of other materials. 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 many Mg die casting applications and are more competitive for smaller items. For these applications, Mg alloys offer the advantages of high fluidity, low specific heat per unit volume, high gate pressures at moderate injection pressures, and low solubility for Fe from the dies.

Wrought Mg alloy products are produced mainly by rolling, extrusion, and press forging at 300-500°C, because 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. Rolled Mg alloy products include flat sheet and plate, coiled sheet, tooling plate, tread plate, and photoengraving plate. Mg-Al-Zn 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. However, Li-containing alloys are not yet in commercial use.

Extrusion is the most commonly used wrought process for Mg alloys. Quality and production rate are affected by the geometry and complexity of a 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.

Forgings represent a relatively small percentage of wrought Mg products and are generally used where the required parts are lightweight, intricately shaped, and exhibit 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.

4.4 SECONDARY FORMING OF WROUGHT PRODUCTS

Primary shapes made of Mg alloys are usually converted (formed) into useful products at elevated temperatures by methods and equipment similar to those commonly employed in forming alloys of other metals. Additional information on Mg forming can be found in Section B.3 of Appendix B. Working of Mg at elevated temperatures has several advantages over cold working, but increases the processing costs significantly. The processes used to form wrought Mg include bending, deep drawing, rubber forming (or hydroforming), stretch forming, spinning, and impact extrusion.

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. Machining may be performed dry, but cutting fluids are sometimes used for cooling.

Superplasticity, by definition, is the capability of certain polycrystalline materials to undergo extensive tensile plastic deformation, often without the formation of a neck, prior to failure. Superplastic forming (SPF) is used to fabricate a wide range of parts, including aircraft parts, architectural shapes, and machine covers. Superplastic alloys are used industrially to manufacture highly complex shapes from sheet. Production of Mg auto parts by SPF at lower temperatures than currently required could conceivably be economical. There is also evidence that SPF may lead to materials with improved ductility. This could be an important factor for automotive uses.

For SPF, the starting sheet is pressed by gas or fluid pressure or by isothermal forging into a die that can be made from inexpensive materials because the pressures involved are modest. This feature is one of the principal economic advantages of SPF when compared with such processes as high-pressure pressing of nonsuperplastic steel sheet. Because of the normally low die costs and relatively slow forming rates, the SPF process is usually economical for small-to-moderate production quantities. Also, the simplicity of the dies and the fact that a single-configuration die (rather than mated die) can be used often permit a short lead time to produce parts once the design is completed. In addition, the accessible strains are much higher in SPF than in ordinary pressing or deep drawing, so that a complex shape can be made in a single forming operation with just one die, rather than a multiple-step process with several dies.

Mg alloys have received relatively little attention in superplasticity research. Most studies have focused on Mg-Li alloys that possess two-phase microstructures and on alloys that contain 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 SPF of conventional wrought Mg alloys. This development could greatly lower the cost of Mg auto part production. More details are included in Section B.6 of Appendix B.

4.5 JOINING

Magnesium can be joined to itself or to other materials by all of the usual methods. An important precaution to bear in mind, however, is that, when Mg is joined to another metal, galvanic corrosion may result unless suitable preventive measures are taken. Care must also be taken in the design of joints to avoid crevices or grooves where water and other corrosive materials could collect.

The room-temperature tensile strength of arc-welded joints in annealed Mg alloy sheet and plate is only slightly lower than that of the base metal, but the strength of arc welds in hard-rolled material is significantly lower than that of the base metal because of annealing effects. Arc welds in some Mg alloys are subject to SCC, and thermal treatment must be used to relieve residual stresses.

Wrought Mg and Al alloys can be spot welded. Spot welds in Mg have good static strength, but lower fatigue strength than riveted or adhesive-bonded joints.

Brazing is possible for some Mg alloys and may have limited nonstructural automotive applications. Dip brazing is recommended, but furnace or torch brazing is possible. Significant property degradation is caused by the high temperatures that are used during brazing. Although soldering is not generally used to make structural joints in Mg alloys, 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 bolts or rivets, and a common concern in all mechanical Mg joints is the use of a dissimilar metal and prevention of galvanic corrosion.

4.6 MAGNESIUM RECYCLING

Recycling of waste materials generated throughout the life cycle of an Mg product is possible; from slags produced during smelting to worn-out auto parts. A schematic diagram that shows the stages of the life cycle of any product is shown in Figure 11. Recycling reduces the impact of waste and recovers useful financial value or energy content from a material. More value is generally recovered from materials that are 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 postconsumer material, either from replacement of parts or, more likely, from scrapping of the entire automobile at the end of its useful life).

4.6.1 Recycling in the Manufacturing Process

Two main types of scrap are present 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

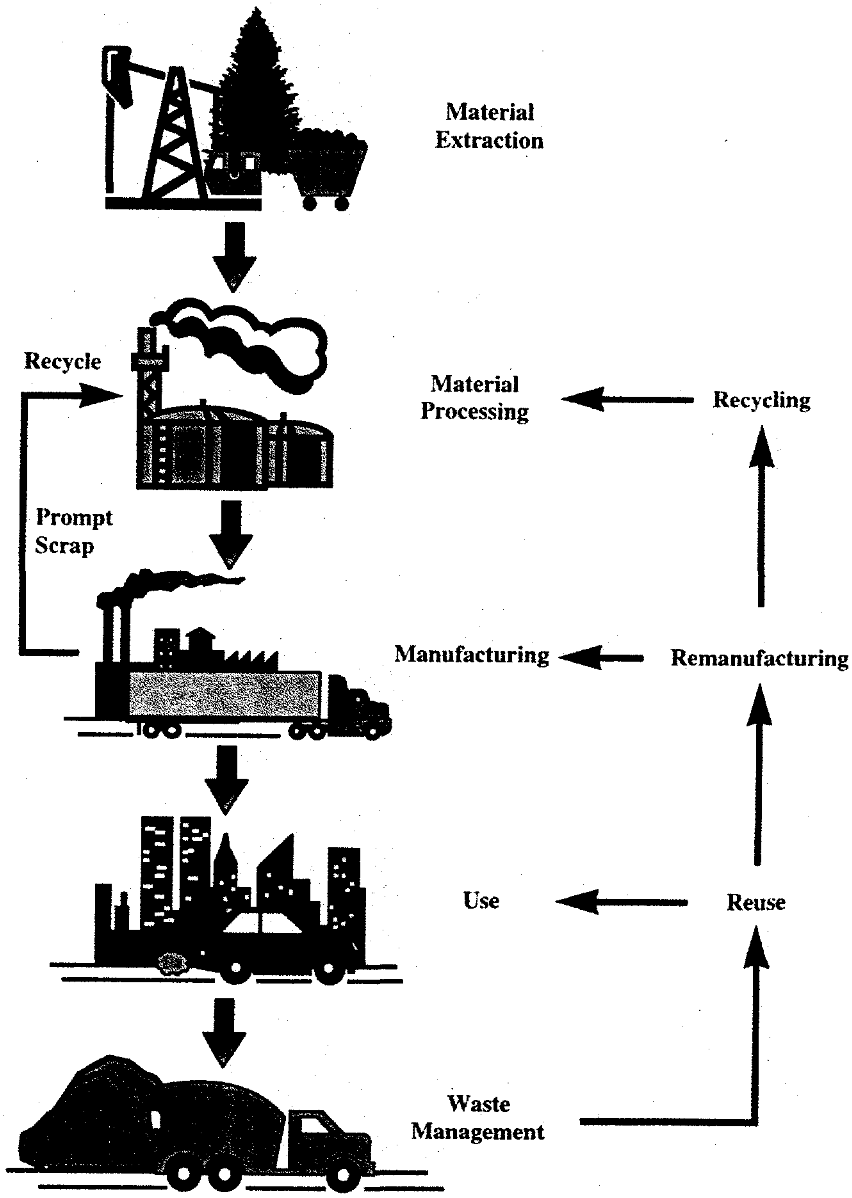

Figure 11. Stages of product life cycle

treated as home scrap and remelted on site (as is often done in high-volume Fe and steel fabrication), for Mg, it is generally sold to a secondary smelter, who then remelts and refines it for resale. Volkswagen, which remelted its own casting scrap from Mg blocks, included 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 product of lower value will result ("downcycling").

The infrastructure for recycling Mg manufacturing scrap is not highly developed. Development is deterred because the U.S. Department of Transportation regulates Mg scrap as a flammable material (appropriate for cuttings and chips only). 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.

4.6.2 Recycling of Postconsumer Magnesium Scrap

Very little Mg per se is currently recycled from obsolete automobiles. The main reason is the economics. The cars now being scrapped average ≈10 years old, so the quantity of Mg in them is low. 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 Cu in the nonferrous stream at the end of the shredding and separation processes. If sufficient quantities were present, it would be possible to separate the Mg from the other nonferrous metals in a sink/float operation, or even manually. However, at this time, the little Mg present 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.[*] If incompatible alloys were used, parts could be marked to show composition, or a computer database could be available to identify materials for a given part and model. The recovered Mg could then either be separated into compatible alloy groups or be used for applications with less demanding composition requirements. However, in contrast with the case of Al, alloy compatibility should not be a major issue for Mg because both cast and wrought parts are likely to use compatible alloys.[**] Shredded Mg could be separated from shredded Al; development of an automated system would be useful. When Mg is used in large volume, recycling will be technically and economically favorable.

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[*] Beetle engines are no longer being scrapped because of high demand for reuse by collectors.

[**] Both would probably use AZ alloys, and ZK alloys could be melted with them (Zr precipitates). Alloy types are defined and discussed in Appendix A.

5 CONCLUSIONS

Two factors inhibit Mg use by U.S. automakers. The first is the perception that it is in short supply, so that automotive use (huge by historical Mg standards) could drive the price rapidly upward. This problem was addressed in a recent paper by Fougner (1994). The second is that the industry has just begun to use die cast Mg products. Industry resistance to the use of lightweight metals in wrought form is strong because there is little experience with their processing. In addition, wrought Mg parts must be hot formed, and this process is not popular with U.S. manufacturers. To understand the seriousness of these problems, consider the general characteristics of the automotive industry.

The automotive business is primarily a manufacturing industry, whose purpose is high-volume, low-cost production of a complex product at extremely sophisticated and capital-intensive manufacturing facilities. Rapid technical developments that bring early obsolescence to costly production equipment are undesirable. Nor can the industry afford to take the risks often associated with new technical developments, because if 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 proved safe and effective elsewhere. Most innovation in the automotive industry comes from suppliers, not from the original equipment manufacturers.

The automotive industry is often criticized as being slow to adopt new technology, particularly by unfair comparison with progressive industries like aerospace or electronics. Aerospace products are often purchased by governments, who may be partners in development, which is a main function of that industry. The electronics industry, on the other hand, thrives on creating new gadgets that consumers "must" have; if these do not work as expected, they are thrown away, because they are inexpensive 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 correction of "mistakes" very costly. As a result, the industry is extremely conservative and adopts only proven, low-risk innovations. Technical resources are devoted to engineering products for cost-effective, trouble-free production, rather than to true R&D.

5.1 POTENTIAL AUTOMOTIVE USES OF MAGNESIUM

Several potential uses for wrought Mg in automobiles have been identified, based on matching the required material properties with those that are available from Mg and its alloys. These uses are listed in Table 9. Significant areas for use of additional castings are also included. Body-in-white substitution potential is based on the Al-intensive Sable with Al replaced by Mg. Relative to the steel-bodied Sable, the saving on the b-i-w is 534/826 or 65%. This is a saving of 17% of the entire Sable weight, and depends on development of an economical hot-forming process and appropriate alloys for the cast nodes of the frame. Total savings from the b-i-w and other parts (which are likely to be used without much R&D) are 750/3170 = 24%. Secondary savings would be expected to raise the total saved to ≈36% of the total auto mass, simply by substituting Mg for steel. Note that the unibody accounts for almost one-half the total saved and therefore is the most obvious target for R&D. A 40% reduction could not be achieved with Mg alone, but probably could with additional use of Al in the engine block.

These applications offer significant potential for weight savings over iron and steel and even over Al; however, barriers must be overcome before these savings can be realized. Technical research areas that would enable increased automotive use of Mg are discussed in the next section, followed by a summary of policy options to further encourage the use of Mg.

Table 9. Estimate of potential for magnesium use in midsized passenger automobile

Component (Number)	Form	R&D to enable	Base mass (lb)	Baseline material	Mass factor	Mass Mg (lb)	Mass saved (lb)
Dash, steering wheel and housing, pedals	Cast	None	105	Fe	3	35	70
Seat frame[a]	Stamped/ extruded	None	75	Fe	3	25	50
Housings, covers	Cast	None	8	Al	1.5	5	3
Wheels (4)[b]	Cast	None	103[c]	40% Al, 60% Fe	1.5	67	36
Suspension links	Extruded	None	60	Fe	3	20	40
Transmission housing	Cast	None	38	Al	1.5	25	13
Subtotal			381	81% Fe, 19% Al	2.2	177	212
Front doors (2)	Sheet	Hot forming	74	Fe	2.5	30	44
Rear doors (2)	Sheet	Hot forming	57	Fe	2.2	26	31
Decklid	Sheet	Hot forming	37	Fe	4	9.5	28
Fenders (2)	Sheet	Hot forming	14	Fe	3.3	4.2	10
Hood	Sheet	Hot forming	49	Fe	3.3	15	34
Unibody	Extruded + cast	Ductile casting alloys	595	Fe	2.9	208	387
Subtotal b-i-w			826	Fe	2.8	293	534
Total					2.6	470	746

[a] Data adapted from Colsanti (1994).

[b] Estimated from Fantetti (1993).

[c] Average mass for current 40% cast Al, 60% fabricated steel market mix.

5.2 RESEARCH NEEDS

The technical problems associated with the manufacture of wrought Mg components can certainly be addressed by research. Some specific R&D areas and their potential benefits are listed in Table 10. A program to make and test a prototype Mg spaceframe or novel hybrid structure, for example, could become the focus of a number of process-related studies (forming, joining, etc.) and bring immediate attention to an underutilized material. A multifaceted R&D program could feature work on new processes for material production and fabrication and identify both problems and opportunities. A more detailed research program, aimed at resolving any problems that are identified, could then be established. The Mg spaceframe could form the core of a super-lightweight body that would have a good chance of reaching the 40% vehicle mass reduction target specified in the Technical Roadmap of the Partnership for a New Generation of Vehicles (PNGV 1995). 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 an 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. Technical questions concerning galvanic corrosion spot welding, adhesive bonding, and forming rate could be resolved during the testing program. Additional promising research areas that could potentially enable increased automotive use of wrought Mg include study of Mg MMCs and SPF (possibly by equal-channel angular extrusion).

Table 10. Recommended technical R&D areas

R&D Area	Benefits
Reduction of MgO in rare-earth chloride electrolyte	Reduce material cost
Hot forming for single-step stamping	Reduce processing cost
Prototype of extruded component	Determine weight reduction and test performance
Improved joining methods	Reduce cost and avoid galvanic corrosion
Improved alloys	Improve material properties, especially creep and ductility
SPF at lower temperatures, higher strain rates	Reduce processing cost
Equal-channel angular extrusion	Reduce costs and improve material properties
Mg metal matrix composites	Improve material properties
Automated scrap separation system	Enable closed-loop recycling to reduce cost and improve supply
Alloy compatibility	Enable easy recycling

Three key economic barriers to widespread Mg use could be overcome by technical advances. These all relate to the high costs of manufacturing standard alloys by conventional processes. First, research could address the high cost of primary Mg production. Development of new production processes, such as that patented for production from MgO, could significantly reduce the material cost. In addition, improved melting and alloy preparation techniques for DC casting under air/SF_6 atmosphere (without the need for flux) would reduce melt losses, environmental problems, and costs. Second, research could be directed at reducing the cost of Mg sheet. Development of a process to cast Mg alloys directly into thin plate, similar to the Hunter-Douglas process for Al, would greatly improve the competitive position of Mg sheet; so could application of high-reduction-per-pass mills to Mg.

Finally, research could be directed at reducing the added costs (relative to other materials) imposed by Mg's physical properties. Although Mg is more corrosion resistant than steel and many Mg castings are used bare or with a simple chrome pickle, surface protection is sometimes an added cost. Therefore, fundamental studies of corrosion behavior in slightly acidic environments and development of better systems for protecting against galvanic corrosion would be useful. It is unlikely that room-temperature forming processes for Mg will be developed, but the costs of forming could be reduced through R&D of economical hot-forming processes. Development of an alloy with higher room-temperature ductility (perhaps by decreasing the grain size) would probably allow reduced forming temperatures, and would also be a boon to spaceframe design. Development of a substitute for the graphite lubricant now used when drawing Mg parts would help reduce costs by avoiding the pickling step needed to remove residual lubricant.

If these areas are addressed, Mg could become a viable contender for high-volume automotive structures. The goal is cost competitiveness on a finished-part basis. Although competitiveness on a per-pound basis is desirable, low density and parts consolidation for more effective design have already enabled the use of Mg steering wheels, instrument panels, and seat assemblies.

5.3 OTHER BARRIERS

For automotive companies to increase their use of wrought Mg significantly, 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. Therefore, the research described above must be completed by others besides the auto companies, e.g., material manufacturers, government laboratories, and universities. Furthermore, the automakers 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 or tax relief could conceivably be offered to encourage investment in the required new equipment. Automakers must also believe that multiple suppliers will be available for wrought Mg.

What other 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 and a price must be ensured that is stable at a level perceived as affordable. A possible policy alternative that would encourage the use of Mg in automobiles would be stricter corporate average fuel economy standards imposed by the government. Recycling could be encouraged by removal of inappropriate regulations.

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[*] Identification of policy options does not imply recommendation for use.

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APPENDIX A:

PROPERTIES OF MAGNESIUM AND ITS ALLOYS

A.1 MAGNESIUM ALLOYS

A.1.1 ALLOYING BEHAVIOR OF MAGNESIUM

Magnesium of purity >99.8% is readily available commercially, but it is rarely used for engineering applications in its unalloyed form. The element is notable for the variety of elements with which it will form solid solutions. The important alloying elements for the lower cost commercial alloys are Al, Zn, Mn, Zr, Si, and rare earths. The higher cost alloys may include Th, Ag, Y, and special rare earths.

Pure Mg is relatively soft and weak, but it can be alloyed with other metals to obtain structurally useful properties. The alloying elements impart improved properties through solid-solution strengthening, dispersion hardening, precipitation hardening, and grain size control. In sheet alloys, strength is also obtained by cold or warm working..

Aluminum is the alloying element most commonly used with Mg. At low concentration (≈3 wt.%), Al strengthens by solid-solution hardening and improves ductility by grain size control. At high concentration (≈9 wt.%), further strengthening is possible by precipitation hardening. Aluminum additions also improve the atmospheric corrosion resistance of Mg. The Mg-Al alloys are generally considered to have good properties at room temperature but they lose their strength rapidly with increasing temperature and are usually not used at temperatures above 130°C.

Zinc imparts strength to Mg by solid-solution and precipitation hardening. Small additions of Zn to Mg-Al alloys also improve corrosion resistance. Zn is also used in combination with Zr, Th, or rare earth to produce precipitation-hardenable Mg alloys with good strength properties. However, Zn increases hot shortness when added in amounts >1 wt.% to Mg alloys that contain 7-10 wt.% of Al. In amounts >2 wt% in these alloys, Zn is likely to cause weld cracking.

Manganese is added in small amounts to Mg-Al and Mg-Al-Zn alloys to improve saltwater corrosion resistance. It has little effect on tensile strength, but increases yield strength slightly. When Al is present, the maximum Mn content seldom exceeds 0.3 wt.%.

Zirconium is a powerful grain refiner for Mg. Unfortunately, it cannot be added to molten Mg-Al alloys because insoluble Al-Zr compounds will form and either all of the Al or all of the Zr will be precipitated from the melt. A similar problem exists with Mg-Mn alloys. There is no similar problem with other Mg alloying elements, so most Mg alloys that do not contain Al or Mn contain a small Zr addition (≈0.6 wt.%) for grain refinement.

Silicon is added to Mg-Al alloys to promote creep resistance at moderate temperatures. The increase in creep resistance is due to the formation of a high-melting-point, finely dispersed Mg_2Si phase at the grain boundary. The nominal amount added is ≈ 1 wt.%.

Rare Earths in the form of mischmetal (50 wt.% Ce, 25 wt.% La, 15 wt.% Nd, 8 wt.% Pr, balance other), are added for strengthening and grain size control. In amounts from 1 to 3 wt.%, the rare earth additions also improve elevated-temperature strength properties.

Silver improves the mechanical properties of Mg alloys. The elevated-temperature resistance of Mg alloys that contain Ag are improved up to 250°C by adding a small amount of Th.

A.1.2 ALLOY DESIGNATIONS AND TEMPERS

Before discussing the properties of magnesium and its alloys it is important to know that "No international code for designating Mg alloys exists, although there has been a trend towards adopting the method used by the American Society for Testing and Materials (ASTM). In this system, the first two letters of the alloy designation indicate the principal alloying elements according to the following code: A - aluminum; C - copper; E - rare earths; H - thorium; K - zirconium; L - lithium; M - manganese; Q - silver; S - silicon; W - yttrium; and Z - zinc. The letter corresponding to the element present in greater quantity is used first, and if they are equal the letters are listed alphabetically. The two (or one if only one alloying element is present) letters are followed by numbers that represent the nominal compositions of these principal alloying elements in wt.%, rounded off to the nearest whole number, e.g., AZ91 indicates the Mg alloy contains 9% Al and 1% Zn, the actual composition ranges being 8.3-9.7% Al and 0.4-1.0% Zn. A limitation is that information concerning other intentionally added elements is not given. Suffix letters A, B, C etc., refer to variations in composition within the specified range, and X indicates that the alloy is experimental" (Polmear 1989). The heat-treated or work-hardened conditions, i.e., tempers, of alloys are specified in Table A-1.

Several Mg alloys, such as Mg-Zn, Mg-Ag, and Mg-rare earth alloys, are amenable to age hardening, although their response is significantly less than is observed with some Al alloys. A feature of the aging process in most alloys is that one stage involves the formation of an ordered, hexagonal precipitate with a $DO_{19}(Mg_3Cd)$ crystal structure that is coherent with the Mg lattice (Polmear 1989). This structure is analogous to the well-known q" (GP zones 2) phase that may form in aged Al-Cu alloys, and it is commonly found in alloys in which the difference in the atomic size of the constituents is large. The precipitate forms as plates or discs parallel to the <0001> Mg directions that lie along the $\{0\bar{0}10\}$ and $\{1\bar{1}20\}$ Mg planes. This structural feature would account for the fact that the phase is relatively stable over a wide temperature range, and it may be the most significant factor in promoting creep resistance in those Mg alloys in which it occurs.

Table A-1. Magnesium alloy temper designations

Temper	Designation
F	As-fabricated
O	Annealed
H-24, H-26	Strain hardened and partially annealed
T4	Solution heat treated
T5	Artificially aged only
T6	Solution heat treated and artificially aged
T7	Solution treated, and stabilized
T8	Solution heat treated, cold worked, and artificially aged

A.1.3 ALLOY TYPES

A.1.3.1 Zirconium-Free Alloys

AZ alloys generally contain 8-9% Al, with small amounts of Zn. The addition of Zn to Mg-AI alloys causes some strengthening, although the amount added has been limited because Zn increases susceptibility to hot cracking during solidification. The most widely used alloy is AZ91C in the form of die castings. The corrosion resistance of Mg alloys is adversely affected by the presence of cathodic impurities such as Fe, Ni, and Cu. Higher purity versions such as AZ91D are found to have corrosion rates that are as much as 100 times lower in salt fog tests than AZ91C (King 1990).

AM alloys were designed for applications where greater ductility and fracture toughness are required. Examples are AM60, AM50, and AM20, which are high-purity alloys with reduced Al content. The improved properties arise because of a reduction in the amount of $Mg_{17}Al_{12}$ around the grain boundaries. Such alloys are used for automobile parts, including wheels, seat frames, and steering wheels.

Cast Mg-Al (AS) alloys show some susceptibility to microporosity but otherwise exhibit good casting qualities and satisfactory resistance to corrosion. They are suitable for use at temperatures only up to 110-120°C. At temperatures up to 150-170°C, alloys with lower Al content (e.g., <4%) that contain 0.8% Si (e.g., AS41 and AS21) show higher creep strength (Westengen 1991, Hollrigl-Rosta 1980, and Waltrip 1990). The performance of AS21 is superior to that of AS41, but it is more difficult to cast because of reduced fluidity due to a lower Al content. The lower Al content also reduces corrosion resistance (Luo 1994). These alloys were exploited on a large scale in the famous Volkswagen Beetle engine.

AE alloys that contain rare earth (RE) elements, added as naturally occurring Ce mischmetal, are only suitable for die castings because slower cooling results in the formation of coarse particles of Al_2RE compounds. One composition, AE42, has a good combination of properties, including creep resistance superior to that of AS alloys. However, use of mischmetal does increase the cost because it is several times more expensive than an equal weight of Si.

ZC alloys respond to age hardening, but they are not amenable to grain refining by superheating or inoculation and are susceptible to microporosity. Consequently, they are not used for commercial castings. Recent work has shown that the addition of Cu to binary Mg-Zn alloys markedly improves ductility and induces a relatively large response to age hardening (Unsworth and King 1984; Lorimal 1986). The Cu-containing alloys exhibit tensile properties similar to alloy AZ91 (e.g., 0.2% yield stress = 130-160 MPa; tensile strength = 215-260 MPa, ductility = 3-8%) but have the advantage that these properties are more reproducible. Elevated-temperature stability is also improved. The addition of Cu to Mg-Al-Zn alloys has a detrimental effect on corrosion resistance, but this appears not to be the case with Mg-Zn-Cu alloys. This difference may be attributed to the incorporation of the Cu in the eutectic phase as $Mg(Cu,Zn)_2$.

Fatigue strength in the unnotched condition (e.g., endurance limit at 10^7 cycles of ± 90 MPa) is better than that of Mg-Al-Zn alloys, while the notched values are comparable. Several Mg-Zn-Cu castings have been produced under practical foundry conditions with sand, gravity die, and precision casting techniques. These alloys offer significant improvements over the traditional Mg-Al-Zn alloys for critical high-strength castings, and may find application in the automotive industry.

A.1.3.2 Zirconium-Containing Alloys

The maximum solubility of Zr in molten Mg is 0.6%, and, because binary Mg-Zr alloys are not sufficiently strong for commercial applications, the addition of other alloying elements is necessary.

ZK alloys can be grain refined, but they are susceptible to microporosity and are not weldable. Commercial products are limited in sand casting, extrusion, and forging.

ZE and EZ alloys overcome the disadvantages of Mg-Zn alloys, which respond to age hardening but have relatively poor casting qualities and are not weldable, because of the addition of rare earth elements. The alloys have good casting properties because the presence of relatively low-melting-point eutectics as networks in the grain boundaries tends to suppress microporosity (Emley 1966). The strength of the alloys may be raised to commercially acceptable levels by adding 0.7% Zr to refine grain size.

The Mg-RE-Zn-Zr alloys, such as EZ33 and ZE41, show good creep resistance up to 250°C and are widely used for castings exposed to elevated temperatures (Lyon 1991). One application of these alloys has been helicopter transmission housings.

HZ and HK alloys exhibit increased creep resistance. Cast and wrought materials that can be used in service at temperatures up to 350°C have been commercially available overseas for some time. As with rare earth elements, Th improves casting properties, and alloys based on the Mg-Th system are also weldable (Emley 1966). The presence of Zn further increases creep strength.

QE alloys are important because the relatively low tensile properties of age-hardened Mg-RE-Zr alloys can be increased by the addition of Ag (Payne 1959). Room-temperature tensile properties are similar to those of the high-strength Mg-Zn-Zr alloys, such as ZK51, with superior casting or welding characteristics. Substitution of normal Ce-rich mischmetal with Nd mischmetal (average composition 80% Nd, 16% Pr, 2% Gd, 2% other) gives a further increase in strength that was attributed to the presence of the Nd. Creep resistance of various Zr-containing Mg alloys is presented in Figure A-1. The most widely used alloy is QE22, which has been used for many aerospace applications, e.g., aircraft landing wheels, gearbox housings, and helicopter rotor fittings (King 1990). Its superior tensile properties over most Mg alloys are maintained to 250°C, although it is only considered to be creep resistant at temperatures up to 200°C. The alloys are relatively expensive, and attempts have been made to replace at least some of the Ag with Cu.

The creep properties of WE alloys may be better than those of either alloy QE22 or QH21 (Mg-2.5Ag-1Th-RE (Nd)-0.7Zr) (Westengen 1991). Two experimental alloys based on Mg-2.5Ag-2RE (Nd)-0.6Zr with additions of 2 and 4% Y have been studied. Room-temperature tensile properties are comparable to those of alloys QE22 and QH21, but the effect of stress on time to produce 0.2% strain at 250°C indicates that the Y-containing alloys show superior creep resistance. This effect has been attributed primarily to solid-solution strengthening in the alloy that contains 2% Y and to modifications to the dispersion of precipitates in the alloy that contains 4% Y.

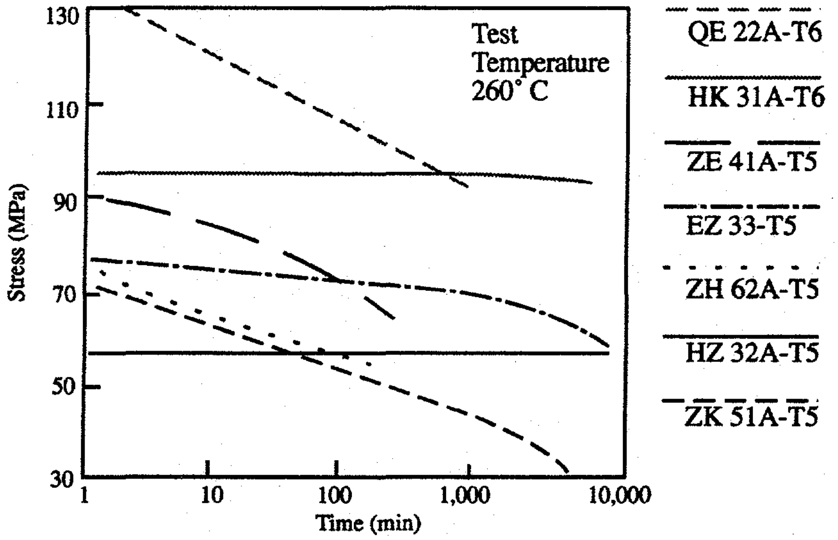

Figure A-1. Creep resistance of various magnesium alloys (Source: adapted from Magnesium Elektron, Ltd., as reproduced in Polmear 1989)

An alloy, designated WE54 (Unsworth 1984), has been developed in Britain that has the nominal composition Mg-5.25Y-3.5RE-0.45Zr. The actual Nd content is between 1.5 and 2.0%. In the 6 temper, typical tensile properties at room temperature are 200 MPa 0.2% proof stress, 275 Mpa tensile strength, and 4% elongation. On long-term exposure at 260°C, the alloy is clearly superior to any of the currently used Mg alloys and is comparable to the best of the Al casting alloys. Corrosion resistance is also superior to that of the other high-temperature Mg alloys and is comparable to the Al alloy A356 (see Table A-2). No evidence of SCC cracking has been detected with stress levels up to 100% of the proof stress.

A.2 MECHANICAL PROPERTIES

A.2.1 TENSILE AND COMPRESSIVE STRENGTH

Table A-3 lists typical strength properties of various forms of Mg alloys, while Table A-4 lists the strength properties of several Mg alloys and those of steel and Al alloys currently used in the automobile industry. The Mg alloy AZ31-H24 exhibits strength properties similar to those of Al-6010, Al-6111, and low-C steel; however, its ductility is only one-quarter that of these alloys. For Mg castings, the compressive yield strength (CYS) is approximately equal to the tensile yield strength (TYS), whereas for wrought Mg alloys, the TYS is greater than the CYS. The ratio of CYS to TYS may be as low as 0.5 in some -0 temper alloys, but typically, it is higher and the ratio may approach 1.0 in very fine-grained, cold-worked alloys.

Table A-2. Corrosion resistance of WE54-T6 and other mag-nesium and aluminum alloy castings after immersion in seawater for 28 days (Source: Unsworth 1984)

Alloy	Wt. loss ($mg/cm^2/day$)
Mg castings	
WE54-T6	0.08-0.2
ZE41-T5, EZ33-T5	2-4
AZ91-T6	6-10
Al castings	
A356, A357	0.04-0.08

Table A-3. Strength properties of commercial forms of magnesium alloys (Source: NMAB 1975)

			Typical Properties			
Form	Alloy	Temper	TS[a]	TYS[b]	CYS[c]	E (%)[d]
Sheet	AZ31B	-0	37	22	16	21
		-H24	42	32	16	15
	ZE10A	-0	33	20	16	20
		-H24	36	26	25	12
Plate	AZ31B	-0	37	22	14	20
		-H24	38	24	16	17
Extrusions	AZ31B	-F	38	28	14	15
	ZK60A	-F	49	37	27	14
		-T5	52	43	31	4
Forgings	AZ61A	-F	43	26	17	12
	AZ80A	-F	46	31	25	8
	ZK60A	-T5	44	31	28	16
Die Castings	AZ91B (or D)	-F	33	23	23	3
	AS41A	-F	30	20	20	6
	AS21A	-F	29	19	19	7
Sand or Permanent	AZ81A	-T4	40	14	14	12
Mold Castings	AZ91C	-T4	40	14	14	11
		-T6	40	19	19	5

[a] TS = tensile strength in ksi.
[b] TYS = tensile yield strength in ksi.
[c] CYS = compressive yield strength in ksi.
[d] E = elongation.

The crystal structure of Mg is close-packed hexagonal, and, at all temperatures, the most important deformation mechanism is slip on the basal plane. Wrought Mg thus acquires a preferred orientation in which the basal planes of individual grains tend to be aligned parallel to the working surface, i.e., the plane of the sheet. Magnesium exhibits a crystallographic deformation mechanism at temperatures ≤200°C, namely $\{10\bar{1}Z\}$ twinning. Twinning shortens the Mg unit cell in the a direction (parallel to the basal plane) and lengthens it in the c direction (perpendicular to the basal plane). With the preferred orientation of sheet being such that the basal planes of the grains are mostly parallel to the plane of the sheet, little twinning occurs when the sheet is stressed in tension, but much twinning occurs when it is stressed in compression. This is why the CYS is lower than the TYS.

Table A-4. Mechanical properties of magnesium, aluminum, and steel alloys

Alloy	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)
Steel[a]			
Low carbon, killed	25	40	40
Structural grade, high strength	40	55	35
Formable grade, high strength	50-80	60-90	30-18
Dual phase, high strength	50	80	25
Ultrahigh strength, HSLA	120-140	125-145	8-4
Aluminum[a]			
5052-H32 (sheet)	28	33	12
5182-H28 (sheet)	35	41	5
6061-T651 (extrusions)	40	45	17
A380 (die cast)	23	47	4
Magnesium[b]			
AZ31B-H24 (sheet)	32	42	15
AZ31B-F (extrusions)	28	38	15
AK60A-T5 (extrusions)	31	44	16
AZ91B (die cast)	23	33	3

[a] Data from Paluszny (1992).
[b] Data from NMAB (1975).

A.2.2 HARDNESS AND WEAR RESISTANCE

The hardness of magnesium alloys is adequate for all structural applications except those that involve severe abrasion. Although rather wide variations in hardness are observed, the resistance of the alloys to abrasion varies by only ≈15-20%. When subjected to wear by rubbing, by frequent removal of studs, or by heavy bearing loads, Mg may be protected by inserts of steel, bronze, or nonmetallic materials attached as sleeves, liners, plates, or bushings. Such inserts may be attached mechanically by pressing, shrinking, riveting, bolting, or bonding; in castings, inserts may be cast in place. Coatings can also be applied to protect surfaces from abrasion.

A.2.3 FATIGUE STRENGTH

The fatigue strength of Mg alloys, as determined with laboratory test samples, covers a relatively wide scatter band. The stress-vs.-number-of-cycles-before-failure (S-N) curves exhibit a gradual change in slope and become essentially parallel to the horizontal axis at 10^7-10^8 cycles, indicating the existence of an endurance limit. The fatigue strengths are greater for wrought products than for cast test bars, and increased surface smoothness improves resistance to fatigue failure. For example, if the relatively rough as-cast surfaces of castings are smoothed by machining, the fatigue properties of the castings are improved. Sharp notches, small radii, fretting, and corrosion are more likely to reduce fatigue life than are variations in chemical composition or heat treatment. The fatigue strength of various Mg alloys, Al, and steel alloys is shown in Table A-5. The fatigue strength of Mg castings (AZ91C-T4) is about the same as that of iron castings currently used as structural parts in automobiles.

A.2.4 MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES

The strength properties of the Mg-Al-Zr and Mg-Zn-Zr alloys are very favorable at room temperature, but decrease with increasing temperature. Elevated temperatures have an adverse effect on the mechanical properties of Mg alloys. This effect may be evaluated by considering yield and tensile strength at elevated temperature after short-term exposure, yield and tensile strength at elevated temperature after prolonged exposure, room-temperature properties after short- and long-term exposure at elevated temperature, and deformation produced by prolonged loading at elevated temperatures (creep). The elevated-temperature yield strength for various Mg alloys is shown in Figure A-2. Elevated-temperature strength, and creep data for many Mg alloys can be found in Busk (1986). For Mg-Al-Zn alloys, an upper temperature limit for practical application is $\approx$120-140°C, and for Mg-Zn-RE-Zr alloys (where RE = rare earth), the corresponding maximum temperature is from 150°C (ZE41-T5) to 250°C (EZ33). Alloys that contain Th, such as HZ31 and HM21, show acceptable strength up to 250 and 350°C, respectively. However, these alloys are relatively expensive and are not available in the U.S. Yttrium-containing alloys such as WE54 and WE43 exhibit long-term creep resistance at 250°C.

A.2.5 DENT RESISTANCE

The resistance of Mg sheet alloy AZ31B-H24 to denting is very high. On the basis of equal weight, AZ31B-H24 is markedly superior in this respect to mild steel and the Al alloys 2024-T3 and 5052-H34 (Busk 1986). On the basis of equal thickness, the denting resistance of this Mg alloy is superior to that of mild steel and Al 5052-H34 and equivalent to that of Al 2024-T3. The high dent resistance of Mg is of great potential value in automotive sheet applications.

A.2.6 DAMPING CAPACITY

Damping is the ability of a material to dissipate vibrational energy rather than transmitting it through the structure, and it is a function of vibration frequency. One measure of the ability of a material to dissipate such energy is the specific damping capacity ψ, which is expressed in terms of percentage as 100 x $\Delta W/W$, where W is the specific elastic energy stored at a given stress

Table A-5. Fatigue strength (ksi) of various magnesium alloys aluminum and steel alloys when stress ratio R = -1

Material	Number of Cycles 10^6	10^7	10^8	$5x10^8$
Steel				
Low carbon, killed	22	—	—	—
Structural grade, high strength	28	—	—	—
Low alloy steel-65NT[a]	32	—	—	—
Ultrahigh strength HSLA	60-70	—	—	—
Gray cast iron 40 (ASTM 48 class)[b]	18	—	—	—
Aluminum				
2036-T4	—	18	—	—
5182-O	—	—	—	20
6010-T4	17	—	—	—
6009-T4	17	—	—	—
A357, 357.0_t62	28	21	17	16
A356-T6 (permanent cast)	—	—	—	12
A380 (die cast)	—	—	—	20
Magnesium				
AZ31-F(extrusion)	23	21	19	—
AZ80 (extrusions)	25	23	22	—
ZK60-F (extrusion)	25	22	20	—
AZ91C-F (casting)	15	14	13	—
AZ91C-T4 (casting)	17	15	14	—
AZ91C-T6 (casting)	15	13	12	—
AM100-T4 (casting)	—	—	—	10
AM100-T6 (casting)	—	—	—	11

[a] 65NT means the steel was normalized and tempered and has a tensile strength of 65 ksi.

[b] ASTM 48 class 40 means the steel has tensile strength of 40 ksi.

amplitude σ. Metallic materials can be divided into high-damping materials ($\psi > 10\%$), moderate-damping materials ($1\% \leq \psi \leq 10\%$), and low-damping materials ($\psi < 1\%$). High damping capacity is desirable in many automotive structural applications.

Pure Mg, especially when cast, possesses a very high damping capacity ($\psi = 60\%$ at $\sigma = 0.1\ \sigma_{ys}$), but its poor mechanical properties make it unsuitable as an engineering material. However, Mg-based alloys that contain 0.4-0.6 wt.% Zr have wide application as high-damping materials. High-damping Mg alloys that contain Mn and Si are also available; the ψ of Mg-0.75 wt.% Si alloy is $\approx$50%, and that of the Mg-0.9 wt.% Mn alloy is $\approx$25%.

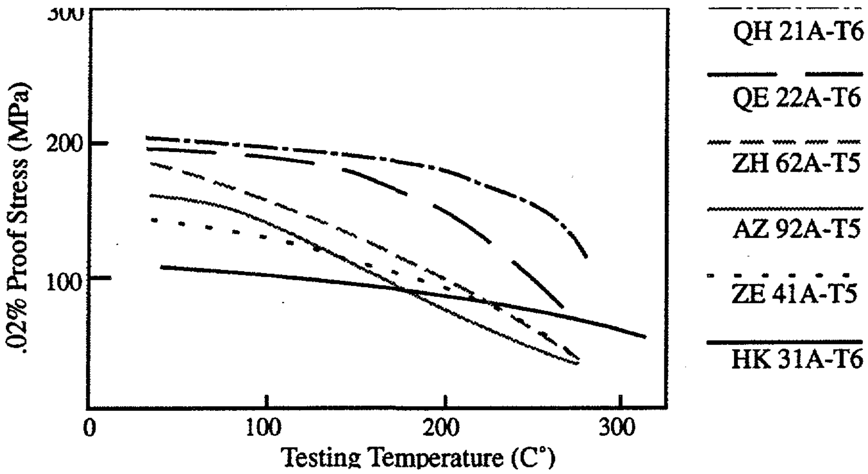

Figure A-2. Elevated-temperature properties for various Mg alloys (Adapted from Unsworth 1977 as cited by Polmear 1989).

The high damping capacity of Mg means that vibrations due to sound or mechanical stress diminish rapidly and are not readily transmitted through the structure. A high damping capacity is particularly desirable when the material is used as a platform for objects sensitive to vibration damage or when sound absorption is important (e.g., noise, vibration, and harshness in automotive applications). The indirect advantages of a high damping capacity can be even more important for Mg as a structural material. Because vibrations due to stress are not transmitted efficiently in Mg, cyclic stresses applied to one part of a structure are significantly attenuated as they are transmitted through that structure. This results in a lower cyclic stress level than if the part were made of another material. This effect can result in a greater fatigue life for the structure than would be predicted from laboratory data.

The best Mg casting alloys are shown in Table A-6 to possess greater damping capacities than either cast iron or selected Al alloys, and they are lighter. Because of their relatively high damping capacity, Mg parts will often survive longer and perform better in vibration environments than will other metals.

A.3 CORROSION RESISTANCE AND PROTECTION

The corrosion resistance of a part depends upon several factors, including environmental conditions, chemical composition of the alloy, its thermal and mechanical history, and the surface condition of the part. In some environments, contact with dissimilar metals can lead to severe damage to the Mg part because of galvanic corrosion unless the joint is properly designed and protected. Because unalloyed Mg is not extensively used for structural purposes, it is the corrosion

Table A-6. Specific damping capacity ψ (%) of magnesium cast and wrought alloys, aluminum castings, and cast iron at various stress amplitudes (Source: Reprinted from Ref. Busk, p. 362, by courtesy of Marcel Dekker, Inc., Copyrighted 1986)

	Stress Amplitude σ (MPa)				
Material	7.0	14.0	20	25	35
Mg Cast alloys					
AZ92-F	0.17	0.45	2.09	5.54	—
AZ92-T4	0.5	1.04	1.29	2.62	3.78
AZ92-T6	0.35	0.70	1.64	3.08	4.78
EZ33A-T5	—	4.88	12.55	18.15	22.42
K1A-F	40	48.8	56	61.7	66.1
HK31-T6	0.37	0.66	1.12	—	—
HZ32A-T5	1.93	7.81	11.64	—	—
Mg Wrought alloys					
AZ31B-F	1.04	1.57	2.2	3.1	4.0
M1A-F	0.35	1.28	2.22	3.14	3.92
Al alloy					
355-T6	—	0.51	0.67	1.0	—
356-T6	0.3	0.48	0.62	0.82	1.2
Cast iron	—	5.0	12.2	14.2	16.5

resistance of Mg alloys that is of interest. Mg alloys, when properly made and selected e.g., high-purity AZ91D, E), are corrosion resistant and can be used successfully in a wide variety of commercial applications. Corrosion problems encountered in service are usually the result of improper design or application or inadequate surface protection.

A.3.1 FUNDAMENTALS

The normal electrode potential of Mg at 25°C is -2.30 V relative to the standard hydrogen electrode potential. This potential places it high in the electrochemical series. Although thermodynamically, Mg should react vigorously with water, it does not do so because very protective films form on the surface. When a freshly prepared Mg surface is exposed to a room-temperature atmosphere, the first film to form is MgO. No additional film forms if no moisture is present, but, in the presence of moisture, the film converts to $Mg(OH)_2$. The CO_2 in the atmosphere dissolves in any condensed water to form carbonic acid, which then reacts with $Mg(OH)_2$ to form carbonates in the film. In a similar manner, the presence of SO_2 in the atmosphere leads to the presence of sulfates (Hanawalt 1972).

Table A-7 shows the corrosion rates of Al alloy 2024, Mg alloy AZ31, and mild steel in three outdoor atmospheres. Magnesium is superior to mild steel but not as resistant as Al. Unlike some Al alloys, Mg alloys are virtually immune to intergranular attack.

The marine corrosion resistance of Mg is highly dependent on both alloy composition and control of impurities (Beck 1940). The three worst impurity elements from the standpoint of increasing corrosion are Fe, Ni, and Cu, and there appears to be a "tolerance limit" for each, depending on alloy composition. For example, the tolerance limit for Fe is lowered by an order of magnitude if Al is present as an alloying element; if Zn is also present, the limit is somewhat higher. The corrosion rate of ZK60A immersed in saltwater is 1.5 mm/yr. and that for AZ31B is 0.6 mm/yr. Small additions of Mn also minimize the adverse effects of these impurities in Zr-free alloys (Goddard 1967 and Olsen 1992). Zirconium has a similar effect on those alloys to which it is added. Special care must be exercised to ensure that Fe scale does not adhere to the surface of wrought products during fabrication. Similarly, emery grit or Fe particles used to shot blast foundry sands from castings can adhere and act as cathodes. Cooling rate and processing conditions may also affect the distribution of impurity (cathodic) phases, thus affecting corrosion rate. It is possible to very closely control impurity levels during Mg production and thus avoid the adverse effects of the impurities.

Mg is also susceptible is galvanic corrosion, which occurs when Mg is connected electrically to a dissimilar metal in the presence of a liquid electrolyte. The most common source of

Table A-7. Results of 2.5-year exposure tests
(Source: ASM 1987)

Atmosphere Material	Corrosion Rate (mm/yr)	Tensile Strength Loss after 2.5 yr (%)
Marine		
Aluminum 2024	0.002	2.5
Magnesium AZ31	0.028	7.4
Mild Steel	0.236	75.4
Industrial		
Aluminum 2024	0.003	1.5
Magnesium AZ31	0.044	11.2
Mild Steel	0.040	11.9
Rural		
Aluminum 2024	0.000	0.4
Magnesium AZ31	0.021	5.9
Mild Steel	0.024	7.5

galvanic corrosion is the coupling of Mg to another metal with fasteners. The problem can be avoided by choosing a compatible fastener, by excluding the electrolyte, by surface finishing the Mg so that it is electrically insulated from the other metal, and/or by redesign of the assembly.

"Magnesium is readily attacked by all mineral acids except chromic and hydrofluoric acids; the latter actually producing a protective film of MgF_2 which prevents attack by most other acids. In contrast, Mg is very resistant to corrosion by alkalis if the pH exceeds 10.5, which corresponds to that of a saturated $Mg(OH)_2$ solution. Chloride ions promote rapid attack of Mg in aqueous solutions, as do sulfate and nitrate ions, whereas soluble fluorides are chemically inert. With organic solutions, methyl alcohol and glycol attack Mg, whereas ethyl alcohol, methylated spirits, oils, and degreasing agents are inert" (Polmear 1989).

Some Mg alloys are susceptible to SCC if subjected to tensile stress and exposed to distilled water, dilute chlorides, and some other solutions. Cracking is primarily transgranular and shows comparatively little relationship to microstructural features such as slip or twinning planes. Mg-Al alloys are most susceptible whereas SCC occurs in the Zr-containing alloys only at stresses that approach the yield stress of the alloy and is not a serious problem. Wrought products are more likely to undergo SCC than castings, and components should be stress-relieved if they are to be exposed to potentially corrosive materials (Polmear 1989).

A.3.2 SURFACE PROTECTION AND FINISHING

Chemical conversion coatings and paint systems have been developed for Mg to improve protection over that provided by the normal $Mg(OH)_2$ surface film and to serve as a better foundation for paint. Anodic coatings are also available; these provide optimum bases for paints. The least expensive finishing system that will provide the needed protection is chosen. Many die cast Mg auto parts are used bare or with a simple chrome pickle. The parts become coated with oil and grease during service and corrosion is negligible.

An excellent review of finishing methods for Mg is given by Busk (1986). Some of the methods are described below. The discussion is derived from Polmear (1989).

Fluoride anodizing involves AC anodizing in a bath of 25% ammonium bi-fluoride, which removes surface impurities and produces a thin, pearly white film of MgF_2. This film is normally stripped in boiling chromic acid before further treatment because it provides a surface that poorly adheres to organic compounds that are used in subsequent treatments.

Chemical treatment involves pickling and conversion of the oxide coating. Components are dipped in chromate solutions, which clean and passivate the surface to some extent through formation of a film of $Mg(OH)_2$, and a Cr compound. Such films have little protective value, but form a good base for subsequent organic coatings.

Electrolytic anodizing includes proprietary treatments that deposit a hard ceramiclike coating that offers some abrasion resistance in addition to corrosion protection, e.g., Dow 17, HEA, and MGZ. Such films are very porous and provide little protection in the unsealed state, but they may be sealed by immersion in a solution of hot dilute sodium dichromate and ammonium bi-fluoride, followed by draining and drying. A better method is to impregnate with a high-temperature-curing epoxy resin. Resin-sealed anodic films are very highly resistant to both corrosion and abrasion, and, in some instances, can even be honed to provide a bearing surface. Impregnation is also used to achieve pressure tightness in castings that are susceptible to microporosity.

Sealing with epoxy resins is accomplished by heating the component to 200-220°C to remove moisture, cooling to $\approx$60°C, and dipping in the resin solution. After the component is removed from the resin solution, drained, and air dried to evaporate solvents, it is baked at 200-220°C to polymerize the resin. This treatment may be repeated once or twice to build up the desired coating thickness, commonly 0.0025 mm.

Standard good-quality paint finishes are applied to the surface of components prepared as in the above-described processes and coated with a chromate-inhibited primer and a good-quality top coat.

Vitreous enameling may be applied to alloys with a solidus temperature that is not too low. Surface preparation involves dipping in a chromate solution before applying the frit.

Electroplating requires several stages of surface cleaning and the application of pretreatments, such as a Zn conversion coating before deposition of Cr, Ni, or some other metal.

A.4 FLAMMABILITY OF MAGNESIUM

When ignited, Mg burns with a very brilliant white light at $\approx$2800°C (Busk 1986). Because it is the Mg vapor that burns, burning requires that the metal be heated to a temperature high enough to produce sufficient vapor to support combustion. This occurs when the metal is melted. The melting temperature of pure Mg is 650°C and that of Mg alloys is somewhat lower. 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. Even if a portion of a Mg part is heated by a torch to the ignition temperature and burning starts, the burning will cease when the torch is removed because heat conduction will lower the temperature of the burning portion below the ignition temperature. However, for finely-divided Mg, such as machining chips, powders, or thin ribbons, the heat from burning will not be quickly conducted away and combustion will continue. The fire that occurs with dry finely divided Mg is typically very slow burning and slow spreading; such a fire is readily handled and extinguished with an approved fire-extinguishing agent. However, with wet finely-divided Mg that is burning, the situation is dramatically different and much more dangerous. The water on the chips decomposes to produce H_2 and O_2, and the H_2 then burns itself, possibly explosively. The result is an intense fire that is not readily extinguished until the Mg is consumed.

Fine Mg suspended in air can explode in the presence of an ignition source. The maximum particle size that will remain suspended in air is ≈ 75 µm, i.e., approximately -200 mesh. Such particle sizes are readily produced by grinding Mg, so an inviolable safety rule in fabricating Mg is that any grinding operation be performed with tools that are equipped with an approved "wet" collector for the dust and that such tools not be used on other metals.

In summary, fire is not a significant hazard for structures made of Mg, even under severe conditions. Operations associated with the preparation of structures, such as machining, grinding, or working with powders, entail some fire hazard. However, this hazard is readily controlled by approved procedures (see Section B.4 of Appendix B).

A.5 CRASHWORTHINESS OF MATERIALS IN AUTOMOBILE STRUCTURAL COMPONENTS

A.5.1 DESIGN CONSIDERATIONS

In the design of automotive structures for crash energy management, two major considerations are the absorption of the vehicle's kinetic energy and the crash resistance, i.e., strength to sustain the crush process and/or maintain passenger compartment integrity.

A.5.1.1 Absorption of a Vehicle's Kinetic Energy

Two basic modes of energy absorption are encountered in thin-walled sheet metal beam-type structures commonly found in automobiles: axial collapse and bending. Because pure axial collapse can only be achieved in the energy-absorbing structures and only during direct frontal/rear or slightly off-angle (5°-10°) impacts, most of the structural members that compose the front- and rear-end structures will be subject to energy-absorbing modes composed of axial collapse and bending. Higher order, more complex modes, which include torsion, are more likely to occur in the structural beam elements comprising the passenger compartment and the structural interfaces that support the energy-absorbing structures. The sheet metal closure/shear and outer-skin panels are likely to collapse by predominantly irregular folding or crumpling.

Axial folding is the most effective mechanism of energy absorption. It is also the most difficult to achieve in real structures because of the instability problems associated with it. Figure A-3 shows a typical stable axial mode of collapse of a square column. In this case, the mode is composed of symmetrically alternating folds. The bending mode, which involves formation of local hinge mechanisms and linkage-type kinematics, is a lower energy mode. That is why structures tend to collapse in this mode. Even a structure designed for axial collapse will fail this way, unless very specific rules are followed to enhance its stability and resistance to off-angle loading. A typical bending mode of collapse of a thin-walled beam-type component is shown in Figure A-4.

In current vehicles, the energy absorption of the front structure is primarily controlled by the behavior of two lower longitudinal rails and two upper side rails (illustrated in Figure A-5), positioned above the front wheels and sometimes referred to as shotguns. In some arrangements, the lower rails provide attachment for the powertrain driveline components. These structures, usually composed of "closed" sections, are connected by an apron, a relatively flat sheet metal closure panel. The rail structures, as they collapse during frontal collision, are designed to develop and maintain force levels that are required to decelerate the vehicle at a rate determined by occupant tolerance. In a well-behaved axial-type collapse, these rails would collapse to ≈25% of their original length. The apron, unless specifically designed to do so, contributes little to energy absorption.

Figure A-6 shows, schematically, a cross section of a front-end energy-absorbing structure, composed of lower and upper rails connected by an apron, in which controlled imperfections ("triggers") in the form of "beads" have been designed into the entire length of all plate elements at a preselected spacing/pitch. Upon impact, this structure will collapse axially in a bellows fashion and will generate an undulating square wave (Paluszny 1992) (a stable constant force during collision, which is desirable). "The height and the pitch of the beads control the size of the folds and, for a given material strength and gage, the nominal/average level of the crush force. Figure A-7 shows an alternative concept of the same energy-absorbing structure, composed again of lower and upper rails and an apron. However, in this concept, called a crush panel, the control of axial collapse, i.e., the fold size and the crush load level, is achieved by shaping the individual sub-elemental panels into a geometric pattern composed, in this case, of the elements of a hexagon. Again, upon impact, this panel will collapse axially with a relatively small fold size, a very high crush efficiency (≈75%), and a very uniform, well-behaved square pulse. The crush load level, in this case, is controlled by the thickness-to-width ratio of the individual hexagonal elements and the material strength. Because of the amount of plastic flow involved in the folding process, materials with high ductility (20-30%) and strain hardening, such as steel, will be the best candidates in both of these design concepts" (Paluszny 1992).

"The structure that supports the energy absorbers (Figures A-6 and A-7), during their collapse and transfers the loads to the passenger compartment will be referred to as the structural interface between the absorbers and the compartment. Its function, from the crash energy management standpoint, is to provide, in the initial stages of a frontal collision, a stable platform for

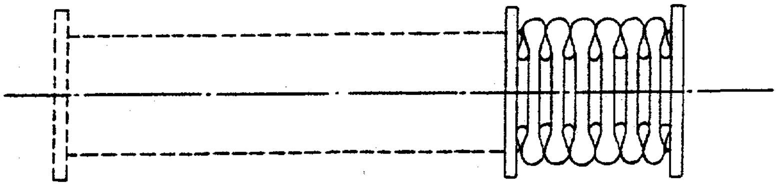

Figure A-3. Axial mode of collapse (Source: Paluszny 1992)

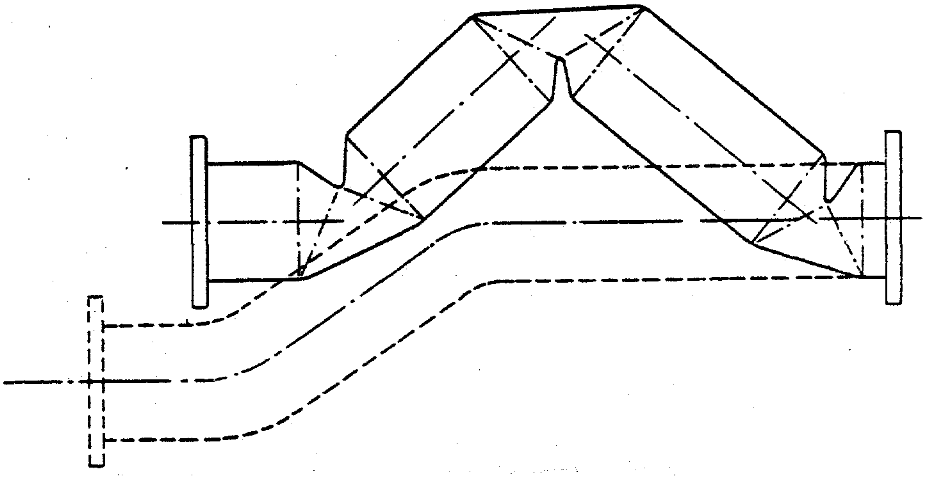

Figure A-4. Bending mode of collapse (Source: Paluszny 1992)

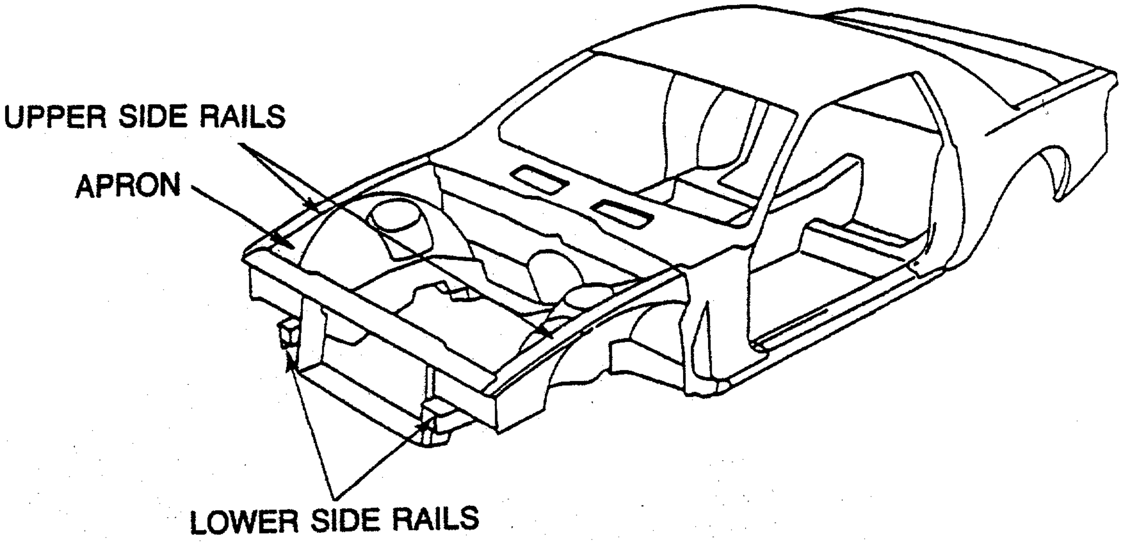

Figure A-5. Major energy-absorbing components in front structure of an automobile (Source: Paluszny 1992)

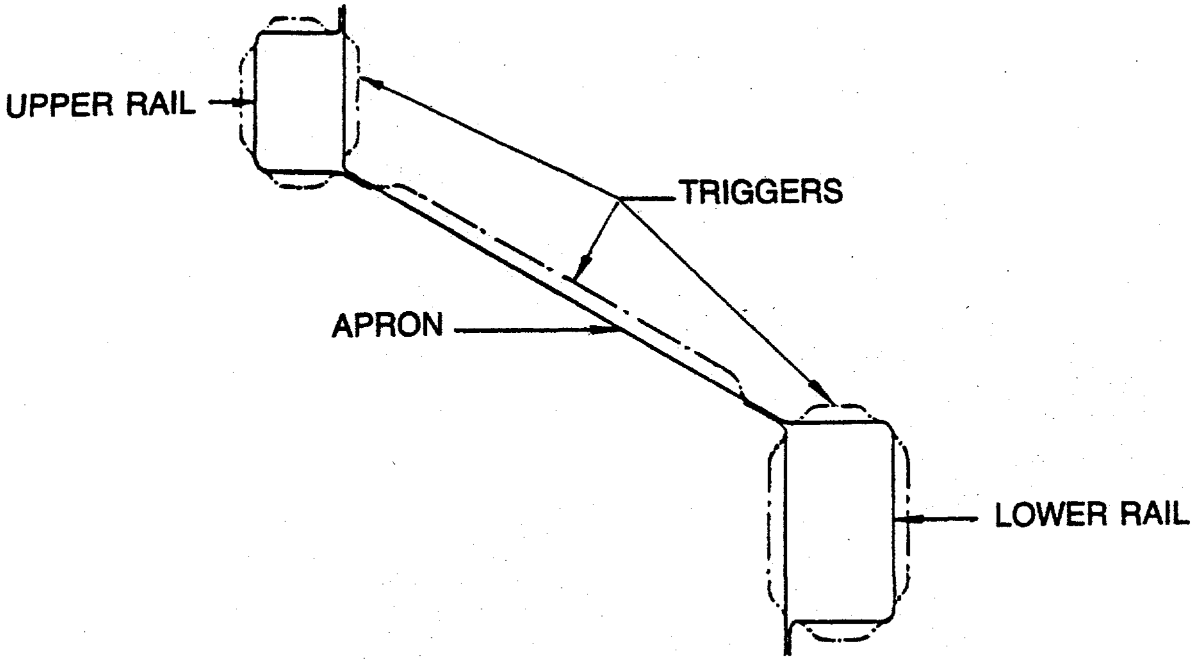

Figure A-6. Front-end energy-absorption structure in which members are triggered for controlled collapse (Source: Paluszny 1992)

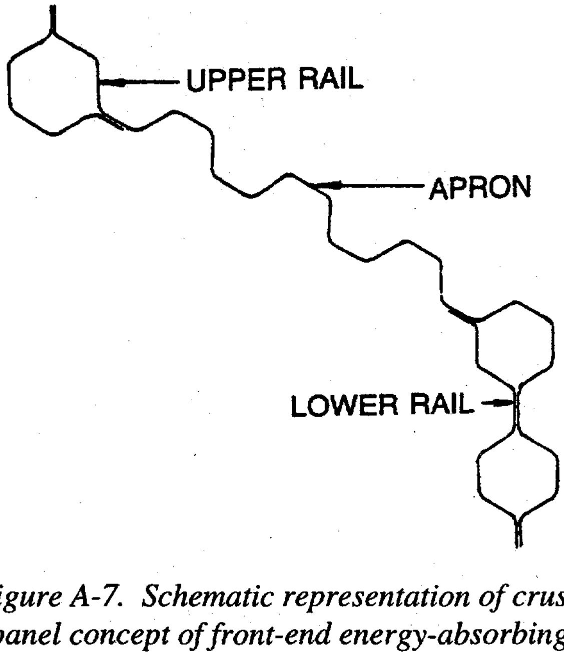

Figure A-7. Schematic representation of crush panel concept of front-end energy-absorbing structure composed of hexagonal elements (Source: Paluszny 1992) the collapsing energy absorbers and to transfer the loads as efficiently as possible (a uniform distribution is most desirable) to the passenger compartment. This structural interface, in turn, collapses as the crash progresses, preferably with a crush-resistance level close to that of the absorbers. The mode of collapse of this structure will depend on the mounting and packaging arrangements of the powertrain/engine compartment componentry, and it will be characterized by crush mechanisms that involve variations of a mixed axial and compound-bending mode. Again, materials with good ductility and relatively high strength (50-80 ksi yield strength) will be the likely candidates for this application" (Paluszny 1992).

"The rear structure is much less demanding than the front structure with respect to crashworthiness. The energy absorption requirements are lower (lower test speeds and lower mass ratios). However, the crush load levels could be higher, but compatible with the integrity requirements of the passenger compartment and the fuel system. From the material selection point of view, the same considerations apply here as in frontal impacts" (Paluszny 1992).

A.5.1.2 Crush Resistance

Axial-Crush Mathematic Model. In general, the average mean crush strength (S_m) and the collapse of plate-type columns will be controlled by a combination of geometry and material properties. Mahmood and Paluszny (1986) developed a quasi-analytical approach to the relationship of crush load to the material properties and structural geometry.

$$\sigma_m = [K_m \, E(t/b)^{0.5}]^n [(1-v^2)\beta \sigma_{ys}]^{-n} \sigma_{ys} \qquad \text{(A-1)}$$

where the crippling coefficient k_m is a function of the degree of restraint at the longitudinal edges, such as that provided by neighboring plates, and is usually expressed in terms of the aspect ratio of the shape of the structural column; the exponent n is influenced by the degree of warping and lateral bending of the unloaded edges (corners); E is Young's modulus of elasticity; v is the Poisson's ratio; σ_{ys} is the yield strength of the material; and β is the material strain-hardening factor. For box-type columns, n has been determined experimentally to be 0.43. For thin-walled sections where $t/b < 0.08$, $\beta = 1$, but β could reach the ratio σ_u/σ_{ys} for a very thick-walled section.

The expression for the mean load-carrying capacity is obtained by multiplying Eq. A-1 by the area of the cross section. Thus, for example, the mean crush load of a square steel column of uniform thickness t and sides b can be expressed as

$$P_m = C t^{1.86} b^{0.14} \beta^{-0.43} \sigma_{ys}^{\;0.57} \qquad \text{(A-2)}$$

where C is the product of the material constants (E,ν) and the geometry factor.

Bending-Crush Mathematical Model. Mahmood and Paluszny (1986) start with the premise that was used in the formulation of the axial-crush-mode model, that bending collapse is initiated by the local buckling of a compressively loaded plate element when the stress reaches the critical value σ_m as given by Eq. A-1, except that the buckling coefficient K_1 has been expanded to cover more general loading and geometry cases representative of vehicle structural components. In their formulation, the buckling coefficient K_1 becomes a product of the crippling coefficient K_m (Eq. A-1), which is a function of the plate aspect ratio (section geometry) and a stress coefficient K_s, which is a function of the applied stress.

$$\sigma_m = [K_1 \; E(t/b)^{0.5}]^n [(1-\nu^2)\beta\sigma_{ys}]^{-n}\sigma_{ys} \qquad K_1 = K_s \times K_m \qquad \text{(A-3)}$$

It is obvious that the crush resistance of the vehicle structure is strongly dependent on the material properties (yield strength σ_{ys}, Young's modulus E, and the strain hardening characteristic β) and the geometry of the structure (thickness t, crippling factor K_m, and n value).

A.5.2 MATERIAL PROPERTIES REQUIREMENTS

To accurately predict the crash performance of a structure or its components, i.e., crush loads, deformations, stability of the crushing process, etc., it is necessary to have reliable material data, and an in-depth knowledge of crush mechanics. This is true whether one uses simple engineering formulations, such as those developed by Mahmood (1986) (Eqs. A-1 and A-3), or elaborate computer models. Because crush mechanisms involve local buckling, which initiates structural crush and is directly related to the modulus of elasticity E (Young's modulus), accurate determination of this modulus becomes very important, particularly in compression. Additional information, relevant to predicting the crash performance of a structure, is the effect of strain hardening and strain aging (when reloading occurs after a period of time) on the strength properties and toughness of the material, that is, its ability to absorb energy when stressed in the plastic range. Toughness is the work of deformation done in stressing the material to the ultimate stress, which is the area under the entire stress-strain curve. Inasmuch as a crash involves dynamic loading, a detailed knowledge of the effects of changing strain rates is vital in predicting the performance of a structure.

It is a widely recognized fact that no two structures, even if they have been produced by the same manufacturing process, exhibit identical properties. Material strength is known to vary not only from batch to batch but within a batch itself, and, in sheet metal products, one occasionally encounters variability in strength properties even within a single sheet. Sheet metal structures are also often sensitive to imperfections (deviations from prescribed geometry) in the sense that their buckling and crippling loads may be severely reduced by these imperfections. Variations in metal thickness are another potential source of uncertainty in the design of sheet metal structures.

In a vehicle crash, the loads imposed on the structure are predominantly those generated by the structure itself as it collapses. These loads, as was shown in Eq. A-1, are directly related to material yield strength ($\approx\sigma_{ys}^{0.57}$) and thickness ($\approx t^{1.83}$). Thus, any variability in material properties and thickness will directly affect the loads imposed on the structure. All of these variations, whether related to material strength or its geometry (thickness), reflect the cumulative effect of various manufacturing processes, which are themselves subject to many random influences, and cause the variability in crush strength and performance of the structure and the crush performance of the vehicle.

The second reason for variability in material properties is environmental effects, notably temperature and corrosion. The mechanical properties of most structural materials are affected by changes in temperature, moisture content (especially for structural polymer composites) and corrosion. Components of the vehicle structure may be subject to temperature changes, depending on geographic location, from ≈-50°F (arctic regions) to 180°F (under the hood). Temperature changes from 70°F down to -50°F and up to 180°F in automotive steels cause 6 and 4% changes in the yield strength and ≈1.5% and 3% changes in the Young's modulus, respectively. Because this change will be directly reflected in either increased crush load or increased crush distance, both of which are detrimental, the actual magnitude of the effect should be verified in a series of controlled tests. Corrosion is a time-dependent effect and will vary with the age of the vehicle.

A.5.3 ALTERNATIVE MATERIAL SUBSTITUTION

The nominal physical/mechanical properties of the 6061T6 Al extrusion alloy and ZK60A-T5 and AZ80A-T5 Mg extrusion alloys are presented in Table A-8, with those of low-C steel and 950 high-strength low-alloy steel. The mechanical properties of Mg and Al alloys are comparable to those of steel, except for their energy absorption capability. High specific strengths, good corrosion resistance and good energy absorption characteristics explain why automotive structural engineers are currently looking at Al alloys, in spite of their high cost, and are likely to become more interested in Mg alloys in the future. Although the specific elasticity of the Al alloy is almost identical with that of steel, in actual structures, it is the absolute elasticity that controls stiffness, and thus the reduction in the modulus of elasticity must be compensated for by corresponding changes in geometry (thickness) (Paluszny 1992). These changes, of course, reduce mass savings.

In the case of panel structures, whose stiffness is a function of thickness cubed, increasing the thickness of an Al panel by 44% will make its stiffness equivalent to that of steel. For beam-type

Table A-8. Mechanical properties of magnesium alloys and various engineering structural alloys relative to steel (Source: ASM 1979)

Stipulation Material	Thickness	Bending Strength	Stiffness	Weight
For equal thickness				
1025 Steel	100	100	100	100
6061-T6 Aluminum sheet and extrusions	100	97.2	34.5	34.5
AZ31B Magnesium extrusions	100	47.2	22.4	22.5
ZK60A-T5 Magnesium extrusions	100	88.9	22.4	22.5
AZ31B-H24 Magnesium sheet	100	73.4	22.4	22.5
For equal bending strength				
1025 Steel	100	100	100	100
6061-T6 Aluminum sheet and extrusions	101	100	35.8	34.8
AZ31B Magnesium extrusions	146	100	69.2	32.9
ZK60A-T5 Magnesium extrusions	106	100	26.7	23.9
AZ31B-H24 Magnesium sheet	117	100	35.6	26.3
For equal stiffness				
1025 Steel	100	100	100	100
6061-T6 Aluminum sheet and extrusions	143	199	100	49.3
AZ31B Magnesium extrusions	165	129	100	37.2
ZK60A-T5 Magnesium extrusions	165	242	100	37.2
AZ31B-H24 Magnesium sheet	165	200	100	37.2
For equal weight				
1025 Steel	100	100	100	100
6061-T6 Aluminum sheet and extrusions	290	817	841	100
AZ31B Magnesium extrusions	444	930	1962	100
ZK60A-T5 Magnesium extrusions	444	1753	1962	100
AZ31B-H24 Magnesium sheet	444	1451	1962	100

structures, the stiffness is related directly to sectional moment of inertia; whereas for box-type, thin-walled sections, the stiffness is proportional to wall thickness. Thus, a threefold increase in gage will be required to make the stiffness of the Al section equal to that of steel. It is estimated that weight savings of 40-50% in the b-i-w and 30% in total vehicle weight should be achievable with Al (Paluszny 1992). Additional savings could be achieved with Mg.

Of interest, however, is how Al or Mg structures perform in collisions, i.e., how well suited Al is for structural crash energy management. Aluminum alloys exhibit physical properties that could meet the very stringent requirements of crash energy management. However, energy absorption by structural deformation requires high strain values or large elongation percentages, and these should be large enough to prevent material separation or crack propagation in a structure, which could lead to an undesirable collapse mode and poor energy absorption. High-strength Al materials require further development to achieve high elongation. Low-strength Al, such as 6061-T4 (σ_{ys} = 21 ksi), has a greater elongation percentage (21%) than 6061-T6, but the lower strength must be compensated for by increasing the thickness of the component to meet the required crush load. This may reduce the effectiveness of Al for weight reduction. Because Mg alloys possess greater specific strength than Al alloys, Mg extrusions have greater potential than Al extrusions for weight reduction, for equivalent crush-loading capability.

Current fabrication of 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 that are 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 generally added to overcome this problem (Paluszny 1992). Another alternative is to use extruded rails instead of ones joined by welding. This option provides an advantage for both Mg and Al alloys in the manufacture of automotive structural components. In practice, steel is difficult to extrude, whereas Mg and Al are easy to extrude and the manufacturing costs are low. Use of extrusions for automotive structural components could be a fruitful area to investigate.

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APPENDIX B:

MELTING PRACTICE AND FABRICATION

B.1 MELTING PRACTICE FOR MAGNESIUM INGOTS

Magnesium ingots, whose production is described in Section 4.1, are commonly melted in mild-steel crucibles during both the alloying and refining or cleaning stages before the material is used to produce cast or wrought components. Unlike Al and its alloys, the presence of an oxide film does not protect the molten metal from further oxidation. On the contrary, it accelerates the process; the oxide continually breaks, exposing fresh metal, which immediately oxidizes. The rate of surface oxidation increases rapidly with increasing temperature above the melting point of 645°C, and, above 850°C, a freshly-exposed surface spontaneously bursts into an intense, white flame. Consequently, suitable fluxes or inert atmospheres must be used when molten Mg and its alloys are handled (Polmear 1989).

B.1.1 THE FLUX PROCESS

The reactivity of Mg limits the choice of fluxes to chlorides and fluorides of the alkali and alkaline-earth metals, including Mg, and to certain inert oxides. During the melting stage, a mixture of halides, $MgCl_2$ with KCl, $BaCl_2$, and CaF_2, is used to protect the metal and wet any oxide/impurity particles in the melt. Prior to pouring, the melt is stirred to promote flux removal of the oxides and halides that are present as a suspension. The removal of halides is essential because of their adverse effect on the corrosion resistance of Mg and its alloys. During pouring, it is common to dust the molten metal with S to minimize oxidation. Flux is effective, but its use results in cost (3-5% of the weight of Mg melts, and metals are lost due to the trapped Mg metal in the sludge) and environmental problems (HCl gas and the disposal of spent sludge).

Magnesium that is to be cast into slabs or billets for wrought products is melted in gas-fired steel crucibles that hold 6000 pounds of molten metal. It is not practical to cover such pots and use an air/SF_6 atmosphere for melt protection, and so the pots are open, with a (molten) flux cover to prevent excessive melt oxidation or burning. A typical melting flux is designated #230 and is a fused mixture of 55% KCl, 34% $MgCl_2$ (anhydrous), 9% $BaCl_2$, and 2% CaF_2. The flux serves to protect the metal and to wet any oxide/impurity particles in the melt, thus causing them to settle to the bottom of the melt. The much greater losses associated with flux melting are the result of entrapment of small globules of metal in the sludge at the bottom of the crucible and difficulty in recovering such metal. Flux works well but its use results in cost and environmental problems, which include

> The cost of the flux itself; the amount of flux used is typically 3-5% of the weight of Mg melted,
>
> The use of flux results in melt loss because Mg becomes trapped in sludge in the bottom of the pot,

The $MgCl_2$ in the flux attracts moisture, which reacts with the melt, and the result is HCl in the atmosphere over the melt; this may cause deterioration of the building that houses the operation,

The sludge in the bottom of the pot, which contains oxides plus spent flux plus Mg, is removed and discarded, and this may present a disposal problem.

B.1.2 THE FLUXLESS PROCESS

During the production of die castings in particular, the presence of a flux can lead to the introduction of flux inclusions in the castings, a circumstance that hinders the greater use of Mg. The development of a fluxless process for use in the melting, holding, and pouring of Mg alloys represents a significant breakthrough. The presence of a small amount of SF_6, a non-toxic odorless gas, in the atmosphere over the Mg melt causes a complete change in the brittleness characteristic of the MgO; with SF_6 present, the MgO becomes extremely elastic and thus protective. The desired level of SF_6 is 0.1-0.5%, depending on melt temperature and other conditions (Pidgeon 1986, Ball 1956, Clow 1992). The use of SF_6-containing atmospheres for melt protection has been embraced by Mg die casters. In their operations, a Mg alloy ingot is simply melted in a covered pot under air/SF_6, and then die cast into parts in a cold- or hot-chamber machine. Run-around scrap is usually sold to a recycler or to a Mg powder producer rather than being remelted in the die casting plant.

Fluxless melting methods have become the preferred approach in the die casting industry, and melting losses have been reduced by almost one-half in some cases. The amount of sludge at the bottom of the crucible is greatly reduced in the fluxless method.

B.1.3 ALLOYING

Most alloying elements are now added to Mg in the form of master alloys or hardeners. Aluminum, Zn, Si, and mischmetal are added to Mg melts as metals. Silicon dissolves somewhat slowly but the others are taken in quickly. Manganese is usually added as $MnCl_2$ (a reducible chloride) and Zr, as a Mg-Zr master alloy. Zirconium has presented special problems, and early attempts to use either Zr metal or a Mg-Zr hardener were ineffective. Success was eventually achieved by adding mixtures of reducible Zr halides, e.g., fluorozirconate K_2ZrF_6, together with large amounts of $BaCl_2$ to increase the density of the salt reaction products (Polmear 1989).

B.1.4 DEGASSING

As with Al, H is the only gas that dissolves in molten Mg, although it causes less problems in Mg alloys because of its comparatively high solid solubility (typically ≈0.3 mL/g). The main source of H is from water vapor in damp fluxes or corroded scrap/ingot, and pickup can be minimized by taking adequate precautions with these materials. A low H content reduces the tendency towards formation of gas porosity, common in Mg-Al and Mg-Al-Zn alloys, and these materials should be degassed with Cl. The optimum temperature for degassing is 725-750°C. Solid $MgCl_2$, which provides little protection from burning, will form if the melt is below 713°C. At temperatures much above 750°C, Mg losses through reaction with Cl become excessive.

Gas porosity is not normally a problem with Zr-containing alloys, because Zr will itself remove H as ZrH_2, and degassing of these alloys is generally unnecessary. However, a degassing treatment does improve the tensile properties of certain Mg-Zn-Zr alloys, presumably by minimizing the loss of Zr as insoluble ZrH_2. In such cases the degassing operation is completed before Zr is added.

B.1.5 GRAIN REFINEMENT

The grain size of the group of alloys based mainly on the Mg-Al system tends to be large and variable. The first method designed to control grain size was to superheat the melt to temperatures >850°C and then quickly cool it to the normal casting temperature and pour. A comparatively fine grain size was achieved with fair success. The superheating effect is only significant in Mg-Al alloys and creates other problems, because crucible and furnace lives are reduced and power requirements are increased.

An alternative technique (the Elfinal process), in which a small quantity of anhydrous $FeCl_3$ is added to the melt, was developed in Germany. Grain refinement is attributed to nucleation by Fe-containing compounds (Emley 1966). This method also has disadvantages because the deliquescent nature of $FeCl_3$ makes its addition hazardous, and the presence of as little as 0.005% Fe in the alloy can adversely affect corrosion resistance.

The grain refinement method currently used for alloys that contain significant Al is to add volatile C-containing compounds to the melt. Hexachlorethane (0.025-0.1% by weight) is commonly used in the form of small briquettes that are held at the bottom of the melt, where they dissociate into C and Cl. Grain refinement is attributed to inoculation of the melt with Al_4C_3, AlN, or Al_4C_3. Release of Cl causes some degassing of the melt, a further advantage of the method (Polmear 1989).

With Mg-Zr alloys, very effective grain refinement is achieved by Zr addition (0.1-0.2 wt.%). The microprobe analyses that have revealed the presence of Zr-rich cores in the centers of Mg grains suggest that Zr may nucleate Mg. The grain size after refining is ≈30 μm.

B.2 FABRICATION OF PRIMARY SHAPES

B.2.1 PRODUCTION OF CASTINGS

B.2.1.1 Sand and Permanent Casting

Magnesium alloys can be cast by both the sand and permanent-mold casting processes. Both methods can produce high-quality castings in extremely intricate shapes, including tubeless passways of complicated design and thin walls, with mechanical properties that are competitive with those of other materials. The costs for both of these processes are high because of the cleaning processes to remove sand and binder and the large amount of metal loss from the runners, risers, and sprues. Magnesium permanent-mold castings can be produced in large volume, but automotive use is unlikely unless an automated method of mold filling, such as a low-pressure casting process, for Mg could be developed that would produce quality parts at fairly low cost. The alloys most likely to be used are AZ91C and AZ81A.

Although the Mg-Al and Mg-Al-Zn alloys are generally easy to cast, their use is limited because they exhibit microshrinkage when sand cast. The Mg-rare-earth-Zr alloys were developed to overcome these limitations. Sand castings in the EZ33A alloy do, in fact, show excellent pressure tightness. The two Mg-Zn-Zr alloys originally developed, ZK51A and ZK61A, exhibit excellent mechanical properties but suffer from hot-shortness cracking and are nonweldable. For normal, fairly moderate-temperature applications (>160°C), the two alloys ZE41A and EZ33A are finding the greatest use. They are very castable and produce very satisfactory castings of considerable complexity. However, sand casting is only suitable for low-volume production, because the cooling rate is slow. Because of the resultant high costs, it is very unlikely that Mg sand castings will ever be used for large-volume automotive applications.

B.2.1.2 Die Casting

Die casting is inherently a low-cost process when large numbers of parts are required. The method is well suited for Zn, Al, and Mg. In the process, molten metal is piston-injected very rapidly into a metal die, where it freezes in the desired part configuration. Some features of the die casting process for Mg are as follows:

> Parts can be cast with high efficiency and low incidence of cracking; because of rapid solidification, the metal is fine-grained and mechanical properties are good,

Magnesium can often be cast on the same machines and into the same dies as Al, with little change in machine injection parameters,

A part die cast in Mg can be cast at significantly higher frequency than the identical Al part, because the heat to be removed by the die (the heat of fusion) for Mg is only two-thirds that of Al,

Magnesium can be cast either on cold- or hot-chamber machines, whereas Al can be cast only on cold-chamber machines;* this is a real advantage for Mg because the hot-chamber process is more efficient and more easily automated than the cold-chamber process.

Magnesium die castings are cost competitive with those of Al, a fact that explains the rapid and consistent growth of their use in automobiles over the last 10 years.

Cold-chamber machines are used for the largest castings, and molten shot weights of 10 kg can now be injected in less than 100 ms at pressures that may be as high as 150 MPa. Hot-chamber machines are used for many applications and are more competitive for smaller sizes, owing to the shorter cycle times that are attainable.

Properties related to castability are fluidity, resistance to shrinkage microporosity and hot tearing, as well as oxidation resistance during melting and casting. Castability increases with increasing Al content due to the improvement of fluidity. However, Al also increases the tendency for shrinkage microporosity because of an increase in freezing range. Zinc also improves fluidity, but high levels of Zn can lead to hot cracking and microporosity problems. Rare earth elements and Th can improve fluidity and resistance to microporosity and hot tearing, but they also result in susceptibility to oxidation problems. The overall diecastability and relative cost of important diecast Mg alloys are summarized in Table B-1. Die castings are normally made from Mg-Al-Zn alloys; the most-used alloys are AZ91B and AZ91D (same alloy with tighter controls on impurity levels). AZ91 and AM60 can be readily cast in thin sections without major problems from hot cracking or lack of feeding. AS41 has a lower Al content and is less fluid; hence, is not easily die cast.

B.2.2 Production of Wrought Products

Ingots from the primary production process are melted, and then cast into appropriate shapes for use in processes that produce wrought products. Wrought materials are produced mainly

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*The injection cylinder and piston of hot-chamber machines are made of a ferrous alloy. During the casting operation, the cylinder and piston are continuously submerged below the surface of the metal being cast; this is not a problem for Mg, but would be untenable for Al because of slow dissolution of the ferrous components by the Al melt.

Table B-1. Characteristics, diecastability, and cost of important diecast Mg alloys (Source: Luo 1994)

Characteristic	AZ91	AM60	AS41	AS21	AE42
Liquidus (°C)	595	615	620	630	625
Solidus (°C)	470	540	565	610	575
Freezing range (°C)	125	75	55	20	50
Diecastability	Excellent	Excellent	Good	Fair	Poor
Cost	Low	Low	Low	Low	High

by rolling, extrusion, and press forging of cast billets or similar shapes at 300-500°C. Rolled products include flat sheet and plate, coiled sheet, tooling plate, tread plate, and photoengraving plate.

"The hexagonal close-packed (hcp) crystal structure of Mg places limitations on the amount of deformation that can be tolerated, particularly at low temperatures. At room temperature, deformation occurs mainly by slip on the basal planes in the close-packed $<11\bar{2}0>$ directions and by twinning on the pyramidal $\{10\bar{1}2\}$ planes (Emley 1966). Above ≈250°C, additional pyramidal $\{10\bar{1}1\}$ slip planes become operative, so that deformation becomes much easier and twinning is less important. Production of wrought Mg alloy products is, therefore, normally carried out by hot working" (Polmear 1989). Some general remarks can be made about the relative properties in various crystalline directions of the final products (Westengen 1991 and Roberts 1960).

(1) "Since the elastic modulus does not show much variation in different directions of the hexagonal Mg crystal, preferred orientation has relatively little effect upon the modulus of wrought products.

(2) Extrusion at relatively low temperatures tends to orient the basal planes and also the $<10\bar{1}0>$ directions approximately parallel to the direction of extrusion. Rolling tends to orient the basal planes parallel to the surface of sheet, with the $<10\bar{1}0>$ directions in the rolling direction.

(3) Because twinning readily occurs when compressive stresses are parallel to the basal plane, wrought Mg alloys tend to show lower values of longitudinal proof stress in compression than in tension. The ratio may lie between 0.5 and 0.7 and, since the design of lightweight structures involves buckling properties which, in turn, are strongly dependent on compressive strength, the ratio is an important characteristic of wrought Mg alloys. The value varies with different alloys and is increased by promoting fine grain size, because

the contribution of grain boundaries to overall strength becomes proportionally greater.

(4) Strengthening of wrought products by cold-rolling in which alternate tension and compression occurs can cause extensive twinning through compression, with a marked reduction in tensile properties." (Polmear 1989).

B.2.2.1 Production of Direct-Chill-Cast Slabs and Billets

Ingots for producing wrought products were formerly produced in permanent metal molds, but semicontinuous direct-chill methods are now in general use. The direct-chill casting of Mg is similar to that of Al in many respects, but there are important differences. With Al, a single large reverbatory furnace is used to prepare the alloy metal, then, all of the metal is cast during a relatively short period of time on an intermittent casting unit with multiple molds. With Mg, it is not practical to prepare large amounts of high-quality molten metal at one time, so the necessary metal is prepared and direct-chill cast continuously. This requires a "flying saw" positioned below the direct-chill mold to cut the casting into the desired lengths as it is being cast. During the direct-chill casting operation, molten metal is pumped into the top of a water-cooled Cu sleeve while solid metal is withdrawn through the bottom. Casting speeds are usually in the range of 2-6 in. per min., depending on alloy composition and ingot size. Round billets for extrusion are usually cast in diameters ranging from 8 to 18 in. Rolling slabs range up to 14 × 43 in. in cross section.

The major defects that occur in direct-chill-cast Mg alloy ingots are cracks, surface laps, and inclusions of flux, oxides, and undesirable metals. These defects are preventable through careful control of molten metal preparation and of casting/cooling conditions. A regular procedure during casting is to remove a cross-sectional slice from the direct-chill casting, fracture it in a prescribed manner, expose the fracture in a high-humidity atmosphere (which causes any flux present to "bloom"), and inspect the fracture for flux, inclusions, porosity, and grain size control. Radiographic and ultrasonic inspection may also be employed. Overall, the cleanliness of the Mg cast for fabrication into wrought products is much better than that of any other cast form.

B.2.2.2 Rolling of Sheet and Plate

An advantage of using Mg flat products in vehicles is the possibility of using increased section thickness without a weight penalty. Thick-sheet construction provides the necessary structural rigidity without the need for costly assembly of ribs and similar strengthening members. If sections of Mg, Al, and steel sheet are rolled and cut to equal weight and area, the thicker Mg sheet will be ≈2.5 times more rigid than the Al sheet and 17 times more rigid than the steel sheet. In actual practice, it is unnecessary to substitute Mg for Al or steel on an equal weight basis. A designer may choose to reduce thickness and sacrifice part of the rigidity to reduce weight, if the part still meets specifications.

The early sheet alloy AZ31B is still the most widely used Mg alloy for applications up to 100°C. AZ31 is strengthened by strain hardening and is weldable, although weldments should be stress relieved to minimize susceptibility to SCC. The Mg-Li system has attracted attention as a basis for very lightweight sheet and plate. Lithium, with a relative density of 0.53, is the lightest of all metals, and the Mg-Li phase diagram shows this element to have extensive solid solubility in Mg. Moreover, only $\approx 11\%$ Li is needed to form a new β-phase, which has a Li-rich body-centered cubic (bcc) structure, thereby offering the prospect of extensive cold formability (Freeth 1954). Finally, the slope of the $\alpha + \beta/\beta$ phase boundary suggests that selected compositions may show age hardening.

Early work on binary alloys revealed that traces of Na caused grain boundary embrittlement, but this problem was overcome with the availability of high-purity Li. A second difficulty was that the binary alloys became unstable and over-aged at slightly elevated temperatures (50-70°C), resulting in excessive creep under relatively low loads. Greater stability has since been achieved by adding other elements, and one composition, LA141 (14wt.% Li, 1wt.% Al), which is weldable, has been used for armor plate and for aerospace components. It has a relative density of only 1.35 and a specific modulus or stiffness (E/ρ), where ρ is density, that is second only to Be. Elevated-temperature stability is further increased by the addition of 0.5% Si (Polmear 1989).

Typical Mg rolling slabs that are 12 × 41 in. in cross section, 75 in. long, and weigh $\approx$2,300 lb are first homogenized at 480 C. The slabs are then continuously hot rolled on an 84-in.-wide, 4-h reversing hot mill to a 0.18-in. thickness in 20-25 passes, depending on sheet width. This part of the rolling process is highly efficient. If sheet thinner than 0.18 in. is required, the material is coiled at 0.18 in. and reduced further by "warm" rolling on a coil mill. The metal is annealed at 340°C before each pass of $\approx$20% reduction. For the final pass, both the metal exit temperature from the mill and the percent reduction are carefully controlled so that the metal is "warm worked" a desired amount. This part of the rolling process is time consuming and progressively conducive to lower metal yields.

Aluminum slabs are hot rolled much like Mg according to similar breakdown schedules. Following breakdown, the rundown to thinner gages is performed cold for Al, with no need for intermediate anneals until very large reductions are accumulated. The rolling costs for Mg in plate or in heavy-gage sheet can, therefore, be close to those for Al of the same thickness. In thin gages, however, Mg requires a more complex rolling procedure with more processing steps than the same gage Al. Scrap losses in Mg are also higher. Magnesium, therefore, does not compete at all well with Al in thin-sheet form.

The most-used Mg alloy for sheet and plate is AZ31B; ZE10A is an alternative alloy that exhibits slightly lower strength properties but does not require stress relief after welding.

B.2.2.3 Extrusion of Alloys

Magnesium extrusions have been used for many applications in the transportation area. In the automobile industry, truck trailers have been explored as a potential end use for Mg extrusions, which have also recently generated much interest for use in passenger car seats. A reduction in weight of 45-80 lb has been achieved for a minivan rear seating bench through the use of a combination of Mg extrusions and die castings.

Extrusion, the most commonly used wrought process for Mg alloys, is used to produce long, straight, semifinished Mg products such as bars; solid, semihollow, and hollow sections; tubes; and wires. Both direct and indirect extrusion presses are used for extrusion of Mg alloys. Pressure is applied hydraulically by a ram to the back of a heated billet and the metal is squeezed through a die into the desired configuration. In indirect extrusion, the die is pushed by a hollow stem, and no relative displacement occurs between the billet and the container. As a result, there is no frictional stress at the billet/container interface. Therefore, the extrusion load and the temperature generated by deformation and friction are reduced. This, in turn, permits an increase in the extrusion speed for the highly alloyed, hot-short Mg alloys. Any extrusion press capable of extruding Al alloys can, after minor modification of tooling, billet temperature, container temperature, and extrusion speed, be used to extrude Mg alloys. An extrusion pressure of ≈850-900 MPa is sufficient for extrusion of most Mg alloys into intricate shapes.

During extrusion of Mg shapes, quality and production rate are affected by several variables, which include the geometry and complexity of the shape, the reduction in area, the alloy being used, the temperature at which the extrusion is being produced, and the design of the die. With a fixed-die design and a given alloy, the temperature of the extrusion and the rate at which the part is produced can be optimized. In principle, the higher the operating temperature, the faster the extrusion rate. However, the billet temperature is limited by the hot-shortness temperature of the alloy being used. The hot-shortness temperature is defined as the temperature at which the lowest melting compound in the alloy begins to melt. This molten material causes the extrusion to tear during extrusion. Frictional forces during the extrusion process will also cause the extrusion to heat and may cause the part to overheat and become hot short. The development of new lubricants that generate less frictional heat, and new procedures for removing Mg from the ram during the indirect extrusion process (perhaps eliminating the frictional force between the billet and the container wall) may be the feasible alternatives for high-rate extrusions.

Extrusion is not considered a net-shape or near-net-shape process. Most Mg extrusions undergo secondary operations before the final part is complete. These secondary operations can be a single warm bending or complex machining and/or painting.

For normal strength requirements, one of the Mg-Al-Zn (AZ) alloys is usually selected. The strength of these alloys increases as Al content increases. AZ31B, a widely-used, moderate-strength alloy with good formability, is used extensively for cathodic protection. AZ31C is a lower purity, commercial variation of AZ31B for lightweight structural applications. The M1A and ZM21A Mg alloys can be extruded at higher speeds than AZ31B, but they have limited use because of their lower strength. Alloy AZ10A, because of its low Al content, has lower strength than AZ31B, but it can be welded without subsequent stress relief. AZ61A and AZ80A can be artificially aged for additional strength, but with a sacrifice in ductility. Alloy ZK60A, which is used where high strength and good toughness are required, is heat treatable and normally used in the artificially aged (T6) condition; however, because its Zn content is high, it is not weldable. The lower-strength ZK21A and ZK40A alloys are more readily extrudable (e.g., 40 m/min) than ZK60A and have had limited use in hollow tubular parts that do not have high strength requirements.

B.2.2.4 Forging of Alloys

Forgings, which represent a relatively small percentage of wrought Mg products, are generally used in situations that require a lightweight part of intricate shape with strengths higher than those that can be achieved with castings. Because Mg is one of the easier materials to forge, the number of forging operations needed to produce finished parts can be greatly reduced. Normally, any forging design produced commercially from Al alloys or steel can also be manufactured from Mg. Press forging is more common than hammer forging, and it is common practice to preextrude the forging blanks to refine the microstructure.

Forgings are made of AZ31B, AZ61A, AZ80A, M1A, and ZK60A. Alloys M1A and AZ31B may be used for hammer forgings, whereas the other alloys are almost always press forged. The strength of AZ80A is greater than that of AZ61A and requires the slowest rate of deformation of the MgAl-Zn alloys. ZK60A has essentially the same strength as AZ80A and greater ductility. To develop maximum properties, both AZ80A and ZK60A are heat treated to the T5 (artificially aged) condition. AZ80A may be given the T6 solution heat treatment, followed by artificial aging to provide maximum creep stability.

Both cast and preextruded billets are used as forging stock. Hydraulic presses are preferred over fast-acting presses because Mg achieves optimum hot ductility when deformed at slower strain rates. Prior to forging, the stock is heated to 330-500°C, depending on the alloy, and the dies are heated to 290-480°C. The Mg is easily worked during the forging operation, and, during the final processing, the temperatures are controlled to induce a controlled amount of cold work in the finished part. The forgings are usually water quenched from the forging operation to prevent further recrystallization and grain growth, and may be aged to the -T5 temper to further improve strength characteristics.

B.3 SECONDARY FORMING OF WROUGHT PRODUCTS

The term forming, as it is normally applied to metals, refers to the various methods of converting primary shapes into useful forms. The room-temperature formability of Mg sheet and extrusions might be described as modest. Some bending, stretching, and drawing operations are possible at room temperature, but, if large deformations are needed, it is common to use elevated temperatures to achieve the desired shape changes. The methods and equipment used in forming Mg alloys are the same as those commonly employed in forming alloys of other metals, except for differences in tooling and technique that are required when forming is done at elevated temperatures. Magnesium can be formed with minor modifications of techniques now in place. There are no technical barriers to the forming of Mg alloys, but the high price of Mg sheet and the high costs associated with hot-forming present economic barriers.

One measure of formability is to bend a material 90° around mandrels of varying radius to find the minimum radius for crack-free bends. Table B-2 presents bend data for Mg sheet (AZ31B, ZE10A) and extrusions (AZ31B, ZK60A) at both room and elevated temperatures. It is readily apparent that sharper bends can be obtained at higher temperatures.

Table B-2. Minimum bend radii for Mg sheet and extrusions at various temperatures (90 ° bend, 99% success rate) (Source: Reprinted from Ref. Busk, pp. 130-131, by courtesy of Marcel Dekker, Inc., Copyrighted 1986)

		Temperature, °C					
Alloy[a]	Temper	20	100	150	200	260	290
Sheet							
AZ31B	-0	5.5	5.5	4.0	3.0	2.0	–
	-H24	8.0	8.0	6.0	–	–	–
ZE10A	-0	3.0	2.0	1.0	–	–	–
	-H24	8.0	8.0	6.0	–	–	–
Extrusions							
AZ31B	-F	2.4	–	–	–	–	–
ZK60A	-F	12.0	–	–	–	–	2.0
	-T5	12.0	6.6	–	–	–	–

[a] Sheet = mandrel radius expressed as multiple of sheet extrusion thickness. Extrusions = mandrel radius expressed as multiple of extrusion thickness.

Another measure of formability is to draw circular sheet blanks of increasing diameter into a cylindrical shape. As a round blank (diameter = D) is drawn into a cup, the metal at the periphery of the blank must be compressed (tangentially) down to the diameter of the cup (diameter = d), so the percentage reduction during the draw is (D-d)/D × 100. At room temperature, Mg sheet strained in this manner will sustain a deformation of only ≈15% before it fails in compression. At higher temperatures, however, much larger reductions can be obtained (see Table B-3). Some advantages for Mg with regard to formability are

> Parts of significant complexity can be drawn at elevated temperature in one operation without repeated annealing and redrawing,
>
> Hardened dies are unnecessary for most types of forming,
>
> Hot-formed parts can be made to close dimensional tolerances because of the absence of springback.

Some disadvantages are

> Both the forming tools and the Mg sheet must be heated.
>
> Better results are obtained at lower forming speeds, i.e., a hydraulic press is preferred to a mechanical press,
>
> Lubrication is required to minimize friction between tools and the work piece; between 120 and 230°C, a soap lubricant is usually satisfactory (it can later be removed by washing in hot water); however, for higher temperatures, colloidal

Table B-3. Drawability (maximum % reduction) of AZ31B-0 at various temperatures and punch speeds[a] *(Source: Reprinted from Ref. Busk, p. 133, by courtesy of Marcel Dekker, Inc., Copyrighted 1986)*

Drawing Temperature, °C	Punch Speed (cm/s) 10	40
20	14.3	—
120	30.3	—
200	58.6	53.8
260	62.5	53.8

[a] Cylinder cup diameter = 76 mm, sheet thickness = 1.65 mm, draw-ring radius = 6 t, punch radius = 10 t.

graphite or molybdenum disulfide may be necessary (removal will probably require a chromic nitrate pickle).

The following processes can be used to form wrought Mg. Elevated temperatures are usually necessary unless the deformations are small.

B.3.1 BENDING

Bending is normally carried out on extrusions. Large radii can be achieved with cold operations, but more difficult work that involves severe radii and deformation of complex sections requires heating to 250-350°C to avoid cracking. Conventional equipment can be used, with suitable heating.

B.3.2 DEEP DRAWING

Mg alloys can be cold drawn to a maximum reduction of 15-25% in the annealed condition. The drawability depends on shape, and this reduction is valid for circular blanks. Square and rectangular boxes are drawn less severely. Both hydraulic and mechanical presses are successfully used for deep drawing. The cold drawability limit of alloy AZ31B-O is ≈20%. Cold-drawn parts are stress relieved at elevated temperature after the final draw, to eliminate the danger of cracking from residual stresses.

Heating of Mg alloys increases their drawability to such an extent that most parts can be made in a single operation. The degree of reduction possible increases as temperature increases. It is practical to draw annealed AZ31B sheet to reductions as high as 68% in a single draw. For most parts, however, depth of draw is not a primary consideration, and no trouble is normally experienced in drawing to the depth required. More problems are encountered in keeping the metal free of puckers in parts with rounded corners or contours. Temperatures above those required for maximum drawability are often necessary to eliminate these puckers.

B.3.3 RUBBER FORMING

Rubber forming (also called hydroforming) of Mg sheets is normally used for production of shallow parts in small quantities, because tooling costs are low. In this process, the sheet is forced with a hydraulic press into a single shaped die by a punch of rubber. Cold forming is possible if generous radii are used, otherwise hot forming is required.

B.3.4 DIMPLING

Dimpling of Mg sheet for flush riveting is normally a hot-forming operation, carried out at 250-350°C to prevent cracking. Undersize holes are first drilled and the sheet is dimpled with a slow-acting press, after which the holes are drilled to size.

B.3.5 STRETCH FORMING

Both Mg sheet and Mg extrusions can be stretch formed. The temper of the alloy has no effect on the techniques employed. Sheet usually is heated to 165-290°C and slowly stretched to the desired contour. Annealed sheet can be stretched at room temperature to a limited extent. However, the formability of alloys of any temper is so much greater at elevated temperatures than at room temperature that elevated-temperature forming is preferred for most operations. Hot-stretch forming produces minimum springback; the little springback that may occur is controlled by adding $\approx 1\%$ to the total stretch.

Wrinkling often is a problem in stretch forming Mg sheet, particularly in making asymmetrical parts of low curvature. The best way to control wrinkling is to build the proper restraints into the dies. Dies may be made of a variety of materials, including Mg alloys, Al alloys, Fe, steel, or Zn alloys. Zinc alloy blocks should not be used above 230°C. Grippers should not have sharp serrated edges, which tear Mg alloys; the use of emery paper between grips and Mg sheet helps to reduce the possibility of tearing.

B.3.6 SPINNING

Spinning of Mg is often carried out cold, except when severe deformation is required. All forms that can be spun cold in pure Al can also be spun in annealed Mg alloy sheet at 250-350°C, with little difference in technique, apart from heating. The basic piece of equipment required for spinning is a lathe. Considerable axial pressure is required in spinning, so a relatively heavy-duty lathe is required.

B.3.7 IMPACT EXTRUSION

Impact extrusion is used to produce symmetrical tubular Mg alloy work pieces, especially those with thin walls or irregular profiles for which other methods are not practical. As applied to Mg alloys, the extrusion process cannot be referred to as cold, because both blanks and tooling must be preheated to at least 175°C. Length-to-diameter ratios for Mg extrusions may be as high as 15:1. Mechanical presses are often used for impact extrusion, because they are faster than hydraulic presses. Impact extrusion is a productive process, and up to 100 extrusions per minute have been achieved, limited only by the press speed.

Heat control is important, and proper arrangement of heating units provides correct heat distribution. In addition to electrical-resistance heating, infrared radiant heating units are also employed. Lubricants are normally recommended, colloidal graphite being best for high-temperature forming. Lower-temperature operations (up to 260°C) may permit the use of heat-resisting waxes and greases or a dry-film stearate-type lubricant instead of colloidal graphite. Because heat significantly affects the properties of hard-rolled Mg, properties of the metal after exposure to elevated temperature must be considered in forming.

B.4 MACHINING

Magnesium and its alloys are the most machinable of all structural materials, with respect to depth of cut, speed of machining, tool wear, relative amount of power required for the equipment being used, or the surface finish obtained. Table B-4 compares machinability of Mg and other metals. There are no significant differences in machinability among Mg alloys.

Because Mg is free cutting, chips produced during machining are well broken. Dimensional tolerances of ≈±0.1 mm (a few thousandths of an inch) can be obtained with standard operations. An outstanding machining characteristic of Mg alloys is their ability to acquire an extremely fine finish, and subsequent grinding and polishing is often unnecessary. Surface smoothness readings of ≈0.1 μm (3-μin.) have been reported for machined Mg and are attainable at both high and low speeds, with or without cutting fluids.

Distortion of Mg parts during machining occurs rarely and usually can be attributed to excessive heating or improper chucking or clamping. Heating of the work is increased by use of dull or improperly designed tools or very fine cuts. Because the coefficient of thermal expansion of Mg

Table B-4. Machinability of metals relative to that of steel (Source: Magnesium Eleckron, Ltd. as reproduced in Polmear 1989)

Metal	Relative Power Required	Rough Turning Speeds ($m \cdot s^{-1}$)	Drilling Speeds 5-10 mm drill ($m \cdot s^{-1}$)
Magnesium	1	up to 20	2.5-8.5
Aluminum	1.8	1.25-12.5	1-6.5
Cast Iron	3.5	0.5-1.5	0.2-0.65
Mild Steel	6.3	0.65-3.3	0.25-0.5
Stainless Steel	10.0	0.3-1.5	0.1-0.35

is relatively high, such excessive heating results in substantial increases in dimensions, particularly in thin sections, where heating causes relatively large increases in temperature. Use of sharp, properly designed tools, coolants, and relatively coarse feeds and depths of cut reduces excessive heating. Wide variations in room temperature during machining also can cause sufficient dimensional change to affect machining tolerances.

B.4.1 CUTTING FLUIDS (COOLANTS)

During machining of Mg alloys, cutting fluids provide far smaller reductions in friction than they provide in machining of other metals and thus are of little use in improving surface finish and tool life. Most machining of Mg alloys is performed dry, but cutting fluids sometimes are used to cool the work. Although less heat is generated during machining of Mg alloys than during machining of other metals, higher cutting speeds and Mg's low heat capacity and relatively high thermal expansion characteristics may make it necessary to dissipate the small amount of heat that is generated. Generation of heat can be minimized by use of correct tooling and machining techniques, but sometimes cutting fluids are needed to reduce the possibility of distorting the work and igniting fine chips. Because they are used primarily to dissipate heat, cutting fluids are referred to as coolants when used in machining of Mg alloys. Numerous mineral oil cutting fluids of relatively low viscosity are satisfactory for use as coolants in machining Mg. Water-soluble oils, oil-water emulsions or water solutions with low hydrogen-evolution properties can be used. Although water-based coolants with low hydrogen-evolution properties are commonly used, water reduces the scrap value of Mg turnings and introduces potential fire hazards during shipment and storage of machine shop scrap.

B.4.2 SAFETY CONSIDERATIONS

The possibility that chips or turnings may ignite must be considered when Mg is to be machined. Chips must be heated close to their melting point before ignition can occur. Roughing cuts and medium-finishing cuts produce chips too large to be readily ignited during machining. Fine-finishing cuts, however, produce fine chips that can be ignited by a spark. Stopping the feed and letting the tool dwell before disengagement and letting the tool or tool holder rub on the work produce extremely fine chips and should be avoided. Wet chips undergo a slow reaction with water, generating hydrogen and heat; the heat buildup could cause ignition, and the hydrogen, if confined, could explode.

Factors that increase the probability of chip ignition are extremely fine feeds, dull or chipped tools, improperly designed tools, improper machining techniques, and sparks caused by tools hitting Fe or steel inserts. Feeds <0.02 mm (0.001 in.) per revolution and cutting speeds >5 m/s (1000 ft/min) increase the risk of fire. Even under the most adverse conditions, with dull tools and fine feeds, chip fires are very unlikely at cutting speeds below 3.5 m/s (700 ft/min). The fire hazards associated with the machining of Mg are easily controlled, and large quantities of Mg are machined without difficulty by following well-established safety precautions (ASM 1979a).

The temperature of chips produced during machining can rise to the ignition point, and once some chips become ignited, the fire can spread to adjacent chips. This necessitates certain precautions during machining.

Keep tools sharp and ground, with adequate relief and clearance angles.

Avoid fine feeds and improper machining techniques such as rubbing the tool on the machined surface or stopping the feed and letting the tool dwell before disengagement.

Do not allow chips to accumulate on machines or on the clothing of operators; store the chips in clean, clearly labeled metal cans.

Keep an adequate supply of a recommended magnesium fire extinguisher (Met-L-X or G-1 powders) within easy reach of operators.

B.5 JOINING

The discussion of joining methods is divided into two sections; the first describes liquid joining methods, such as welding, and the second describes mechanical methods, such as riveting.

B.5.1 LIQUID JOINING

B.5.1.1 Welding of Magnesium Alloys

Virtually all Mg welding is performed with the inert-gas-shielded tungsten arc or consumable electrode process. The shielding gas should be either He or Ar. Magnesium wrought alloys are welded readily by gas metal-arc welding and by resistance spot welding. The relative weldability of Mg alloys is shown in Table B-5. A relatively small amount of heat is required to melt Mg because its melting point, latent heat of fusion, and specific heat per unit volume are comparatively low. On an equal-volume basis, the total heat of fusion is approximately two-thirds that of Al and one-fifth that of steel. The lower heat capacity and heat of fusion of Mg, when compared with those of Al, imply that the power inputs can be lower and the welding speed can be higher than for welding Al. However, the high coefficients of thermal expansion and conductivity

Table B-5. Relative weldability of magnesium alloys (Source: ASM 1983b)

Alloy	Rating Arc Welding	 Spot Welding
Cast		
AZ63A	C	–
AZ81A	B+	–
AZ91C	B+	–
AZ92A	B	–
EZ33A	A	–
QE22A	B	–
ZE41A	B	–
WE43	B-	–
WE54	B-	–
ZC63	B-	–
ZK51A	D	–
ZK61A	D	–
Wrought		
AZ10A	A	A
AZ31B,C	A	A
AZ61A	B	A
AZ80A	B	A
HM21A	A	B
ZE10A	A	–
ZK21A	B	A
ZK60A	D	A

[a] A-Excellent, B-Good, C-Fair, D-Limited weldability.

and low elastic modulus of Mg alloys tend to cause considerable distortion during welding. In this respect, the fixturing required for the welding of Mg is very similar to that needed for Al. However, it must be more substantial than for the welding of steel.

The thermal and electrical conductivity of Al is approximately twice that of Mg and four times greater than that of steel. Consequently, higher heat inputs are required when Al is fusion welded. For resistance spot welding, higher current density and shorter weld time are needed for Al than for Mg and steel of equivalent thickness. The linear coefficient of thermal expansion of Al is approximately identical with that of Mg and about twice that of steel. However, the melting range of Mg and Al alloys is roughly one-half that of steel. Therefore, the total expansion during welding of identical Mg and/or Al and steel components would be about equal, because the differences in their coefficients of thermal expansion and melting ranges tend to balance each other. However, stress-relief treatment is more critical in Mg than in Al.

Arc welding of Mg. Rods of approximately the same composition as the base metal generally are satisfactory for the arc welding of Mg alloys, although the use of a more highly alloyed rod with lower melting point and wider freezing range is sometimes beneficial to minimize cracking. Butt and fillet joints are preferred in Mg because they are the easiest to make by arc welding, and they provide more consistent results than other types of joints. Lap joints sometimes are used, but generally are less satisfactory than butt joints for load-carrying applications. Most Mg cast and wrought alloys can be successfully arc welded, except the alloys that contain more Zn, such as ZK60A (wrought alloy) and AZ63A, ZK51A, and ZK61A (cast alloys).

The room-temperature tensile strength of arc-welded joints in annealed Mg-alloy sheet and plate is lower than that of the base metal (joint efficiencies > 90%). Tensile strengths of arc welds in hard-rolled material, however, are significantly lower than those of the base metal (joint efficiencies of only 65-85%) as a result of the annealing effect of welding. Consequently, the room-temperature strength of arc-welded joints in Mg alloy sheet and plate is about the same regardless of the temper of the base metal.

Arc welds in some Mg alloys, specifically the Mg-Al-Zn series and alloys that contain >1% Al, are subject to SCC, and thermal treatment must be used to remove the residual stresses that cause this phenomenon. The parts are placed in a jig or clamping plate and heated at certain temperatures for specified times. After heating, the parts are cooled in still air. The use of jigs is sometimes necessary so that relief of stresses does not result in warpage of the assembly. The other types of Mg alloys, including those that contain Mn, rare earths, Th, Zn, or Zr, are not sensitive to stress corrosion and normally do not require stress relief after welding.

Spot welding of Mg. Wrought Mg and Al alloys can be spot welded, but castings are not normally resistance welded. Spot welds in Mg exhibit good static strength, but fatigue strength is lower than that of either riveted or adhesive-bonded joints. Spot-welded assemblies are used mainly for low-stress applications and are not recommended where joints are subject to vibration. Typical shear strengths of spot welds in three alloys are given in Table B-6. The strength of seam welds of the continuous or intermittent type is comparable to that of spot welds.

The Mg-Al-Zn alloys, alloys with 1% Zn, and alloys that contain rare earths or Th as the major alloying element are most weldable. Alloys with Zn as the major alloying element are more difficult to weld because they generally have a wide melting range, which makes them sensitive to

Table B-6. Typical single-spot shear strength (lb) of magnesium alloys (Source: ASM 1979)

Material thickness (in.)	Avg. spot diameter (in.)	Alloy		
		AZ31B-O sheet	HK31A-H24 sheet	M1A-F extrusions
0.020	0.14	220	–	105
0.032	0.18	330	300	210
0.064	0.24	750	720	500

hot cracking. However, ZK21A and ZK60A can be spot welded readily, which may be an advantage for the automotive industry where most joining is accomplished by spot welding.

Surface cleaning is important during spot welding of both Mg and Al. Any surface contamination will inhibit wetting and fusion. Careful preweld cleaning is essential for the production of spot welds of consistent size and soundness.

B.5.1.2 Brazing of Mg

Although not a common joining method, 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. Mechanical cleaning of the joint, sometimes followed by chemical cleaning, must be thorough for a good brazed joint. The flux used for the bath must melt at a temperature lower than that of the brazing alloy, promote flow of the molten brazing alloy, and protect the assembly from oxidation during the brazing step. It must not contain any oxygen-containing compounds such as nitrates because these can react violently with the Mg. If the brazing alloy being used is in the form of a powder, it must be mixed with a volatile organic material to form a paste. The paste is placed in the joint, the assembly is preheated, and then put in the brazing flux. Because brazing is carried out at a high temperature, degradation of properties is significant.

B.5.1.3 Soldering of Mg

Soldering is not recommended for Mg for two reasons. First, the alloys used for solder, when in contact with Mg, cause severe galvanic corrosion problems. Second, the alloying between the Mg and the solder results in the formation of brittle compounds, making the joint weak. For these reasons, soldering is not generally used to make structural joints in Mg alloys, although it can be used for special purposes, such as repair of photoengraving plates, soldering for electrical contacts, and the filling of dents, seams, and surface irregularities prior to painting. The latter application is of possible relevance for automotive sheet applications.

B.5.1.4 Adhesive Bonding of Mg

Adhesive bonding of Mg has become an important and extremely versatile joining method, being suitable for the joining of any form or size of Mg to almost any other material. Because the metal is not disturbed, as by drilling or melting, there are no stress concentrations. Because the adhesive has a low modulus of elasticity, it will not transmit stress as readily as a "stiffer" joint. Thus, the method is especially suited for those applications that require good fatigue strength. Adhesive bonding permits the use of thinner materials than can be effectively riveted. The adhesive fills the spaces between the contacting surfaces and thus acts as an insulator between any dissimilar metals in the joint, therefore, there is no danger of galvanic corrosion. It also permits manufacture of assemblies with surfaces that are smoother than those associated with riveting.

With the extensive development that has occurred in adhesive technology, a wide choice of adhesive types, strengths, and application methods is available to the designer. All types can be applied to Mg, and adhesives with specific properties can be sought from manufacturers. Table B-7 lists a few that have been used for Mg joining. Techniques specific to Mg relate to curing temperatures and times, and to surface preparation. Most adhesives require a curing time at an elevated temperature. It is important to ensure that the times and temperatures used do not decrease the mechanical and corrosion properties of the Mg alloys being bonded. The effect of temperature on the shear strength of adhesive-bonded joints in Mg and Al alloys is shown in Table B-8.

Proper surface preparation prior to application of the adhesive is important. This can be simply cleaning off oil and grease followed by sanding. However, for best results, the surface should be prepared in the same way as for applying paint, by use of chemical-conversion or anodic coatings. The shear strength of the adhesive is, in general, greater than that of a conversion coating or a paint film. Therefore, the films applied during surface preparation should be thin, commonly ≈0.003 mm (0.0001 in.) or less for conversion or anodic coatings, and 0.008 mm (0.0003 in.) or less for paint films.

B.5.2 MECHANICAL JOINTS

Mechanical joints include rivets, screws, bolts, self-clinching devices, and interference fits. Because Mg is not suitable for the joining material, such as a bolt or rivet, a common factor in all mechanical joints for Mg is the use of a dissimilar metal. The possibility of galvanic corrosion thereby introduced must be guarded against in the preparation of all of these joints. The methods of protecting against galvanic corrosion must be employed when metallic fasteners are used.

Table B-7. Characteristics of adhesives used for magnesium (Source: ASM 1979)

Composition	Temp (°C)	Curing time (s)	Pressure (MPa)	Shear strength (MPa)
Phenolic rubber-base resin	160	32	0.3-3.5	15-18
Epoxy resin paste plus liquid activator	95	30	contact	20
Rubber base	200	8	contact	12-16
Vinyl phenolic	150	50	varied	7-12
Epoxy-type resin	95	15-45	0.1	8-12
Modified epoxy resin	175	60	contact	19-30
Phenolic	150	15	0.2	16

Table B-8. Effect of temperature on shear strength (MPa) of phenolic rubber-based resin-adhesive-bonded magnesium and aluminum alloys (Data from ASM 1979)

Temperature	Alloy	
(°C)	AZ31B-H24	Al-2024
0	20	26
50	13	17
100	8	12
150	7	9
200	6	8

B.5.2.1 Riveting

The riveting of Mg is not much different from the riveting of other materials. Selection of the rivet material and protection of the joint are important. Rivets should be no closer together than three rivet diameters, and no closer to the edge than 2.5 rivet diameters. The edge should be smooth and free from any defects introduced by shearing. If this is not the case, the edge distance must be increased to three times the rivet diameter.

B.5.2.2 Bolting

Bolts or studs can be threaded or cast directly into Mg, in which case the threads should be coarser and more rounded than those used for steel or Al. Aluminum alloy 6061, if sufficiently strong, results in the least galvanic corrosion. If steel must be used for strength, the bolts should be plated with Al, Zn, Sn, or Cd to minimize galvanic corrosion problems.

Magnesium's high coefficient of thermal expansion relative to other metals requires special consideration if interference inserts will be used in structures that then serve at elevated temperatures. It may be necessary to increase the room-temperature interference to retain adequate holding power at the elevated temperature.

Various locking and self-clinching nuts can be used satisfactorily on Mg with no changes from the procedures used with other metals. Washers at least three times the bolt diameter should be used under both bolt heads and nuts, and should preferably be of a compatible Al alloy such as 5052 or 6061, provided the torque is sufficiently low that the Al will not deform. The washers serve two purposes: to prevent damage to the Mg surface as the fastener is tightened, and to minimize galvanic attack, if Al is the washer material.

B.6 SUPERPLASTICITY OF MAGNESIUM ALLOYS

B.6.1 FUNDAMENTALS

A glass rod, heated by a torch and pulled by hand, will stretch out into a long, uniform fiber. The strain of the glass can be several thousand percent without fracture. A bar of mild steel, however, when pulled in a tensile machine, will neck down locally and break after a strain on the order of tens of a percent. The glass, unlike steel, behaves superplastically. Recent studies have shown that not only polycrystalline metallic alloys, but also intermetallic compounds and ceramics, are capable of being pulled in tension or pressed in compression to very high stains (elongations on the order of hundreds or even thousands of a percent) if certain microstructural characteristics exist and optimized deformation processing procedures (temperature and strain rate) are applied (Baudelet 1991).

Superplasticity, by definition, is the capability of certain polycrystalline materials to undergo extensive tensile plastic deformation, often without the formation of a neck, prior to failure. The first description of superplasticity in metallic material was reported by Bengough (1912), who observed that a special brass exhibited a maximum elongation of 163% at 700°C. An elongation-to-failure of 7550% was claimed in the Pb-Sn system in 1988, and a new record of 8000% in commercial aluminum bronze (Sherby 1989) was reported shortly thereafter. Such extreme elongation values are the exception, and most superplastic alloys exhibit optimum tensile elongations of 300-1000%. This range of values is more than sufficient to permit the fabrication of extremely complex shapes by superplastic forming (SPF) technology. Many of these products only require 200-300% elongation.

Three major conditions are required for superplasticity: a fine, stable grain size (usually $<\approx 10$ μm average diameter), a deformation temperature above approximately one-half the absolute melting temperature of the alloy, and a controlled strain rate. The specific parameters for optimum SPF processing must be established for each alloy. The differences in selected deformation parameters (flow stress σ, elongation e_f, and strain-rate sensitivity m) between superplastic and conventional deformation in metallic alloys are summarized in Figure B-1. Flow stress σ is strongly dependent on strain rate $\dot{\epsilon}$ at the superplastic temperature. At lower strain rates (Region I of Figure B-1), a relatively mild dependence of s on $\dot{\epsilon}$ and low values of e_f and m are observed. With increasing strain rate, the strain-rate dependence of flow stress becomes stronger, and the values of e_f and m increase. A transition to Region II occurs where the superplasticity effect attains its maximum. The range of strain rates that corresponds to Region II varies somewhat for different alloys, but is usually from 10^{-4} to $10^{-2}s^{-1}$. Subsequent increases in strain rate (Region III) lead to a decrease of e_f and m. The strain-rate-sensitivity exponent m provides a measure of the strain rate sensitivity of flow stress and is defined as $m = \delta\ (\ln\sigma)/2(\ln\dot{\epsilon})$. This strain-rate-sensitivity exponent is a measure of the resistance to local plastic instability for a material, and it correlates with total elongation for materials that do not fracture prematurely. Superplasticity occurs when elongations $>\approx 200\%$ are observed, and superplastic alloys typically exhibit m values between ≈ 0.3 and 1.0 ($m = 1$ for glass).

Grain size d is the most important structural factor that affects the superplastic effect, because a stable microcrystalline structure ($d < 10$ μm) is an essential condition for realizing superplasticity. Figure B-2 (Salama 1987) shows the effect of grain size on the processing parameters for an Al-10 wt.% Mg-0.1 wt.% Zr alloy. With a fine-grained structure, the alloy is superplastic at relatively low temperatures (300°C), when compared with other superplastic Al alloys (see Table B-9). A coarse-grained alloy ($d = 40$ μm) exhibits a maximum m value of 0.33 and maximum elongation of only $\approx 200\%$, whereas a fine-grained alloy ($d = 3$ μm) exhibits an m value that approaches 0.5, with a maximum elongation of 500%. The elongation of several superplastic alloys is shown as a function of strain rate in Figure B-3 (Sherby 1989), where high strain-rate superplasticity is achieved by decreasing the grain size of the alloys. The effect of grain size on superplastic behavior suggests the feasibility of decreasing the processing temperature and time, which would make the application of superplasticity very attractive to the cost-conscious automotive industry.

Superplastic forming is used to fabricate a wide range of items, including aircraft parts, architectural shapes, and machine covers. Superplastic alloys are used industrially to manufacture highly complex shapes from sheet. The starting sheet is pressed by gas or fluid pressure or by isothermal forging into a die that can be made from inexpensive materials because the pressures involved are modest. This feature is one of the principal economic advantages of SPF when compared with high-pressure pressing of nonsuperplastic steel sheet. Because of the normally low die costs and relatively slow forming rates, the SPF process is economical for small-to-moderate production quantities. Also, the simplicity of the dies and the fact that a single-configuration die

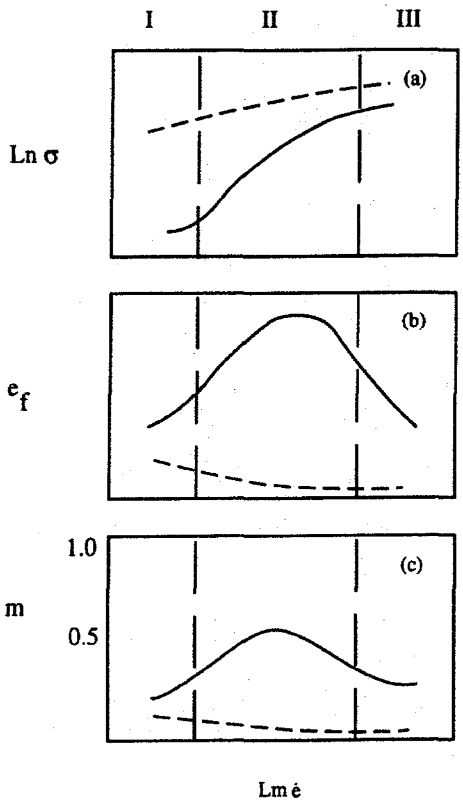

Figure B-1. Typical strain-rate dependence of selected deformation parameters in superplastic and conventional deformation: (a) flow stress, (b) elongation, (c) strain rate sensitivity; superplastic deformation, solid line; conventional deformation, dashed line (Adapted from Kaibyshev 1992)

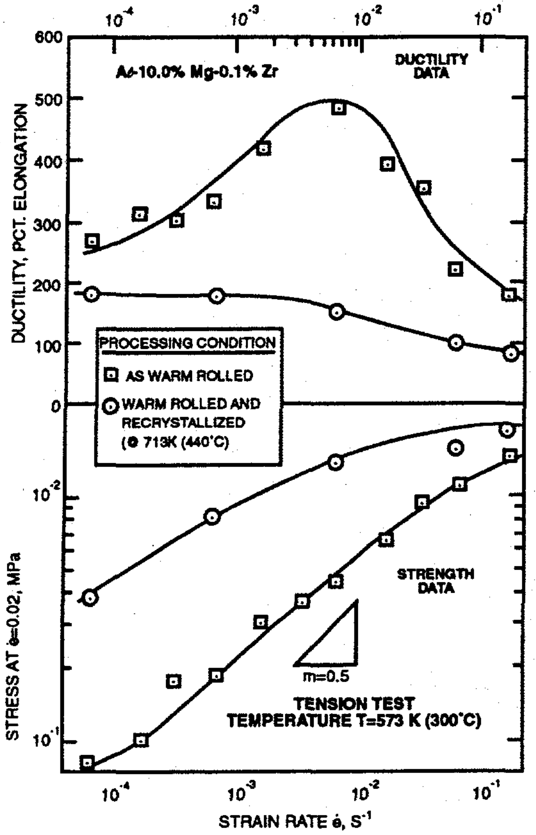

Figure B-2. Ductility and flow stress-strain rate of fine-and coarse-grained Al-10 wt.% Mg-0.1 wt.% Sr alloy at 300 °C (square, fine grain; circle, coarse grain) (Adapted from Salama 1987, as reproduced in Sherby 1989).

Table B-9. Summary of superplastic characteristics of several alloys[a]

Alloy	SP temperature (°C)	Elongation %	Strain rate s^{-1}	m[b]
1. Ti-6wt.%Al-4wt.%V	927	1000-2000	2×10^{-4}	0.8
2. Al-4.5wt.%Cu-0.5wt.%Zn	450	600-1000	2×10^{-3}	0.38
3. Al-4.5wt.%Zn-4.5wt.%Ca	565	500	2×10^{-3}	0.3
4. Al-8090	515	610	2×10^{-1}	–
5. Al-7475 + 12-15wt.% SiC_w	520	350	2×10^{-4}	>0.5
6. Al-2024 + 20wt.% SiC_w	475	300	10^{-4}	1.0
7. Al-7475	516	600-1200	2×10^{-4}	0.75
8. Zn-22wt.%Al	200	200	2×10^{-2}	0.5
9. Fe-1.5wt.%C-1.5wt.%Cr	650	1200	2×10^{-4}	0.46
10. Fe-26wt.%Cr-6.5wt.%Ni	900	1000	2×10^{-5}	–
11. IN-100 (Powder Metallurgy)	1010	1000	–	0.5
12. Mg-1.8wt.%Mn-0.25wt.%Ce (MA8)	400	300	4.1×10^{-2}	0.4
13. Mg-1.6wt.%Cd-3.1wt.%Zn-0.65wt.%Zr-0.95wt.%La (MA15)	450	300	4.1×10^{-2}	0.45
14. Mg-8.1wt.%Li-5.2wt%Al-4.7wt.%Cd (MA21)	450	475	4.1×10^{-2}	0.55
15. Mg-8.5wt.%Li	350	610	4×10^{-4}	0.4-0.65
16. Mg-9wt.%Li	150-250	460	3×10^{-4}	0.52
17. Mg-1.86wt.%Al-0.8wt.%Zn	400	345	8.3×10^{-4}	–

[a] Data for Alloys 1-3 and 7-11 from Encyclopedia of Mater. Sci. Eng. (1986). Data for Alloys 4-6 from Baudelet (1991). Data for Alloys 12-14 from Kaibyshev (1992). Data for Alloy 15 from Higashi (1991). Data for Alloy 16 from Meternier (1990). Data for Alloy 17 from Hatta (1992).

[b] m = Strain rate sensitivity exponent.

(rather than a mated die) can be used often permit a short lead time to produce parts after the design is completed. In addition, the accessible strains are much higher in SPF than in ordinary pressing or deep drawing, so that a complex shape can be made in a single forming operation with just one die, rather than requiring a multiple-step operation with several dies.

The metallurgist must develop alloys that are fine-grained and resist coarsening at the temperature of optimum superplasticity. This can be accomplished either by designing a duplex microstructure with two phases, both equiaxed in form and present in roughly equal proportions, or by dispersing a small fraction of a second phase in finely-distributed form. In the "duplex" case, most of the boundaries are interphase boundaries, which can behave similarly to ordinary monophase grain boundaries when sliding but not when migrating. In the "dispersed" case, the fine particles (which are too small to cause serious cavitation and premature fracture) pin migrating boundaries sufficiently to prevent rapid coarsening of the grains but not enough to prevent grain boundary migration altogether, a delicate balance.

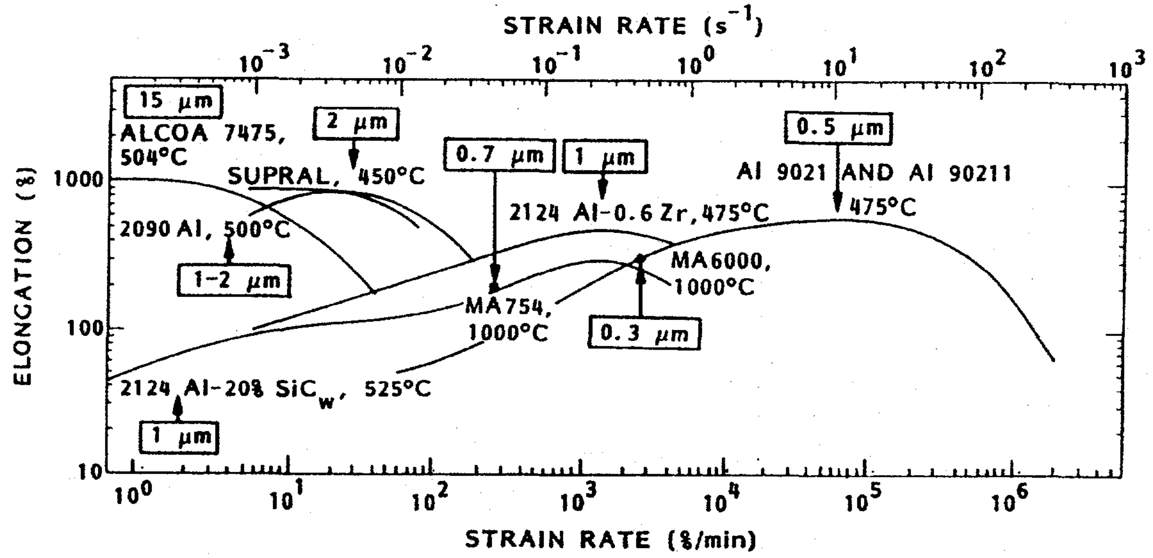

Figure B-3. Superplastic behavior as a function of strain rate for a range of grain sizes in aluminum based alloys (Reprinted from Progress in Materials Science, Vol. 33, O. Sherby and J. Wadsworth, Superplasticity–Recent Advances and Future Directions, p. 189, Copyright 1989, with kind permission from Elsevier Science, Ltd., The Boulevard, Langford Ridlington OX51GB, UK)

Another possibility is to maximize the strain rate at which m remains high enough to enhance plasticity (if not provide superplasticity) so that forming can be accomplished rapidly; the lowest acceptable rate is $\approx 10^{-2}$ s^{-1} for economical industrial production. This rate is still much lower than for other forming processes. In addition, a reasonably wide temperature range for superplastic working is needed, because it is not practical to hold a large sheet within narrow temperature limits. It is thus desirable to have a range of (small) grain sizes, because each grain size has different optimum values of temperature T and strain rate $\dot{\epsilon}$.

B.6.2 SUPERPLASTICITY OF MG ALLOYS

Little research has been done on superplasticity of Mg alloys. The few studies that have been reported concentrated on the superplastic behavior of Mg-Li dual-phase alloys, because a fine-grained two-phase structure can be produced relatively easily. Sherby (Meternier 1990) investigated the effect of grain size on the superplastic behavior of a Mg-9 wt.% Li alloy. Fine-grained structures were made in the form of laminates by foil-metallurgy techniques in which the alloys were heavily cold rolled and press bonded to laminates at low temperature. These laminates, with grain size of 6-35 μm, exhibited superplastic behavior at $\approx$300°C and strain rates of 10^{-4}-10^{-3} s^{-1}, with a rate sensitivity m of 0.5 and an elongation-to-failure of 460%. Other laminates (Taleff 1992) with a smaller grain size (2.7 μm) exhibit superplastic characteristics at even lower temperatures ($\approx$100°C), with an m value of ≈0.5 and an elongation-to-failure of 450%. It was postulated that superplastic flow in the sample with a grain size range of 6-35 μm is controlled by grain boundary sliding, accommodated by slip with lattice diffusion. In the sample with smaller grain size, superplastic flow is also controlled by grain boundary sliding. However, in this case it is accommodated by slip with grain boundary diffusion rather than slip with lattice diffusion.

Wofenstine et al. (Higashi 1991) studied the effects of initial microstructural conditions on the superplastic behaviors of Mg-Li alloys and found that a binary Mg-8.5 wt.% Li alloy, with an initial unrecrystallized microstructure, exhibited superplasticity at 350°C. A maximum elongation-to-failure of 610% and an m value of ≈0.5-0.7 were measured at a strain rate of 10^{-4}-10^{-2} s^{-1}. This elongation is greater than the 460% value exhibited by a Mg-9 wt.% Li (Meternier 1990) alloy with a fully recrystallized microstructure prior to deformation. The microstructure of the unrecrystallized alloy changed during deformation from an elongated banded structure to fine equiaxed grains for both the a and b phases, and the grain size after failure was ≈10 μm. These increases in strain-rate sensitivity and elongation-to-failure and the change in microstructure suggested that the Mg-Li alloy underwent continuous dynamic recrystallization during superplastic deformation; the microstructure may be more stable in the unrecrystallized alloy than in the fully recrystallized alloy because of the dynamic recrystallization processing.

Valiev and Mukherjee (1992) studied deformation mechanisms in a Mg-1.5 wt.% Mn-0.3 wt.% Ce alloy (designated MA8 in the Russian nomenclature system, which will be used below when the Russian results are described) with a mixed fine- and coarse-grained structure. They found that the coarse grains deform by dislocation slip, whereas grain boundary sliding occurs in the fine-grained area. They also predicted that a transition from superplastic to nonsuperplastic behavior would occur if the volume fraction of fine grains was <40%.

Hatta (1992) investigated the possibility of grain refinement by predeformation to achieve superplasticity in a Mg-Al-Zn (Mg-1.86 wt.% Al-0.8 wt.% Zn-0.05 wt.% Mn) alloy. They found that the Mg-Al-Zn alloy with the smallest grain size (≈8 μm) can be achieved by prestraining the specimen to ≈60-70% at 250°C with a strain rate of $10^{-4}s^{-1}$. No superplastic behavior was observed at this temperature. However, with this small grain size, possible superplasticity is observed at 400-450°C, with elongations-to-failure of 200% at strain rates of ≈10^{-5}-$10^{-3}s^{-1}$. Grain refinement by predeformation exerts a positive effect on the superplasticity of Mg-based alloys. However, especially for the AZ alloys in which $Mg_{17}Al_{12}$ precipitates form, particles at the grain boundaries are too coarse and too weak to pin movement of the boundaries, and grain growth is still a substantial barrier for superplasticity. This implies that the addition of a grain-refining element or other effective grain reduction methods are necessary for high superplasticity in the commercial alloys like Mg-Al-Zn.

Solberg (1991) examined the superplasticity of the Mg-Zn alloy AZ91. The fine-grained structure (1.2 ± 0.4 μm) was obtained through a rapid solidification process followed by extrusion at elevated temperature. Elongations well above 1000% seem easily attainable with this microstructure at ≈275-300°C. The microstructure proved to be very stable at elevated temperature. However, superplastic deformation was observed to lead to a decrease in room-temperature strength and ductility. This effect is probably due to the high density of pores, which act as crack initiators, formed during superplastic straining. Mabuchi (1993) studied the superplasticity of the Mg-Zn alloy AZ91 produced by the extrusion of machined chips. A fine-grained (7-μm) structure was developed by the extrusion process, and a maximum elongation of 230% was observed at 300°C with a strain rate of $3.3 \times 10^{-4}s^{-1}$. In addition, a good combination of strength and ductility was observed at room temperature.

Systematic studies of the effects of chemical composition, initial microstructure, microstructural stability, and dynamic recrystallization on the superplastic behaviors, anisotropy, and mechanical properties of various Mg alloys were carried out by Kaibyshev (1992) at the Institute of Metal Superplasticity Problems of the Russian Academy of Science. Alloys selected included MA8, MA15, and MA21.[*] The results can be summarized as follows:

> These alloys, with initial grain sizes of 15 μm, exhibit superplasticity from 350 to 450°C, with a strain rate of $\approx 10^{-2}s^{-1}$. Elongations are in the range of 300-450%. The effect of chemical composition (alloying) is manifested indirectly through microstructural stability. Highly alloyed material (e.g., MA15), exhibits microstructural stability to higher temperatures than low-alloyed material (MA8). The alloy MA21's better superplastic behavior (high m, elongation, and stability) is attributed to the presence of a more favorable microstructure (eutectic dual-phase structure).
>
> The effect of initial microstructure (grain size) on superplasticity was studied with the MA15 alloy at four initial grain sizes (80, 20, 9, and 4.5 μm). This alloy is unusual in that there is an optimal grain size (9 μm) that produces the best properties at high temperatures. This is atypical because smaller grain size generally improves superplastic parameters. This peculiarity is probably due to effects on microstructural stability, which in turn depend on the quantity of second phases in the alloy. A reduction in grain size is accompanied by an increase in

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[*] MA8 (Mg-1.8 wt.% Mn-0.25 wt.% Ce) that contained a small number of dispersed second-phase particles, was considered low alloyed. MA15 (Mg-1.6 wt.% Cd-3.1 wt.% Zn-0.65 wt.% Zr-0.95 wt.% La), with a large amount of various elements both in solid solution in Mg and in the other phases, is categorized as highly alloyed. MA21 (Mg-5.2 wt.% Al-4.7 wt.% Cd-8.1 wt.% Li-0.2 wt.% Mn-1.38 wt.% Zn) possesses a dual-phase microstructure with similar volume fractions of a phase (Mg-rich, hcp structure) and b phase (Li-rich, bcc structure).

grain boundary area, which, in turn, requires many dispersed second-phase particles to maintain microstructural stability.

The effect of dynamic recrystallization on the superplasticity of Mg-alloys was studied in as-cast MA14 (Mg-6.0 wt.% Zn-0.65 wt.% Zr) and MA21 alloys. These alloys begin to exhibit superplastic behavior with different specific volumes of recrystallized grains. The lower the deformation temperature, the greater the volume fraction of recrystallized grains required to transform the alloy to a superplastic state. Temperature played an important role in the development of dynamic recrystallization in the Mg-Li alloy MA21. At higher temperatures (≈350°C), this alloy exhibited superplastic behavior after recrystallization had been accomplished only in the b phase, whereas at lower temperatures (250°C), complete recrystallization of the Li (b phase) failed to transform the alloy to a superplastic state. In these materials, dynamic recrystallization is an effective grain-refining method that enables simultaneous refinement of the microstructure and achievement of superplastic behavior.

The effect of superplastic deformation (compared with other thermomechanical treatments) on the subsequent mechanical properties of Mg alloys was studied with the highly alloyed MA15. Three different thermomechanical treatments were used: hot-pressed forging, hot-pressed forging followed by annealing, and SPF. The results showed that SPF resulted in an increase in room-temperature ductility (25%). In addition, the ratios of the yield to ultimate strength and of the ductilities in the longitudinal and transverse directions were very close to unity after SPF. This means that a highly isotropic structure was formed after superplastic deformation.

The effect of SPF on precipitation-hardening behavior and its thermal stability was studied with the Mg-Li alloy MA21. Three thermomechanical processes (hot-pressed forging, hot-pressed forging followed by solution heat treatment at 350°C and natural aging, and SPF followed by quenching and natural aging) were performed. When compared with the other two processes, the room-temperature strength of the Mg-Li alloy was significantly increased after superplastic deformation. Mg-Li alloys exhibit weak creep resistance even at ambient temperature; however, the properties of the superplastically deformed MA21 alloy, after holding at room temperature for three years, were the same as those found immediately after superplastic deformation. Following superplastic deformation and quenching, finely-dispersed precipitates of q phase ($MgLi_2X$, where X is Al, Cd, or Zn) were uniformly distributed throughout the b grain interior. No coarse particles were observed in the grain and interphase boundaries.

However, for the material that was solution treated after hot-pressed forging, the distribution of q-phase precipitates within the b-grains was highly nonuniform; coarse precipitates were present within the grains and in the near-boundary zone. The formation of a uniform equilibrium structure is one possible reason for the observed improvement and stabilization of the mechanical properties of the Mg-Li alloys after SPF.

B.6.3 ASSESSMENT OF MAGNESIUM ALLOY SUPERPLASTICITY

Most studies have focused on Mg-Li alloys with two-phase microstructures that are favorable for superplasticity and on alloys that contain rare-earth elements, such as La, Ce, etc., that produce finely-dispersed precipitates that can stabilize a fine-grained structure during superplastic deformation. Few Mg-Al-Zn alloys (AZ series) have been investigated. The superplastic temperatures for the alloys studied were ≈250-450°C and the strain rates were 10^{-4}-10^{-2} s^{-1}. Elongations of as much as 610% were obtained for a Mg-8.5 wt.% Li alloy. The initial grain sizes of the Mg alloys used in these investigations were in the range of 1-20 μm and were produced by various techniques, such as static recrystallization, dynamic recrystallization, rapid-solidification processing, and thin-foil processing. Backofen et al. (1968) achieved grain refinement in the Mg alloy ZK60A (Mg-0.5% Zr) and reported elongations of 1700% at 310°C and $10^{-2}s^{-1}$. No other study of superplasticity of commercial wrought alloys has been published.

Magnesium alloys exhibit poor room-temperature formability because their hexagonal close packed (hcp) crystallographic structure results in few active slip systems. Warm forming increases the formability of Mg alloys by increasing the number of active slip systems, but the maximum elongation never exceeds 80%, even at elevated temperatures. For complex geometries that require multiple-step forming, SPF is beneficial in that not only can high elongations be achieved in a singe operation without intermediate annealing, but complex die sets and tooling can be replaced with simple, low-cost die configurations. This means that fabrication costs can be reduced. However, SPF for Mg alloys is still in the laboratory stage. A processing-parameter database for the various alloys has not been systematically established. To use SPF cost-effectively for Mg alloys in the automotive and aerospace industries, intensive research is needed in the following areas.

A homogeneous fine-grained structure with high stability is essential for superplastic deformation. Cold straining followed by recrystallization annealing leads to grain size refinement in the low Mg-based alloys, but only yields grain size down to ≈10 μm. In addition, while it is possible to create a fairly homogeneous structure with large prestrain in sheet, recrystallization annealing of bulk samples results in a range of grain sizes that is very difficult to eliminate by increasing the level of prestraining. Dynamic recrystallization has shown promising results with respect to grain refinement, but the mechanism is still unclear. The effects of temperature, strain rate, prestrain, alloying elements, initial microstructure, and texture on the processing in terms of the diffusion mechanisms and dislocation motion for various Mg alloys are the keys to understanding the dynamic recrystallization process and the optimum control of the microstructure.

In principle, the smaller the grain size, the better the superplastic parameters (low flow stress, low temperature, high strain rate and high resistance to localized necking). Rapid solidification processes and powder metallurgy (nanocrystalline) processing can produce a fine-grained structure of submicron size. However, these processes are expensive, because of the extra costs associated with the high-vacuum equipment required to prevent reaction between the powder and air and moisture, and the costs of facilities for achieving extremely rapid quench rates. In addition, safety concerns are more critical when dealing with fine Mg powder, and explosions may take place because H_2 gas is generated. Another limitation for these processes is the difficulty in producing submicron-grained samples in bulk form. Accordingly, severe plastic deformation processes may play an important role in the development of fine-grained Mg alloys for SPF. Valiev et al. (1991) produced a fine-grained structure of ≈ 0.3 μm in alloy MA8. This process, however, is impractical because of its high pressure and its size limitations.

Equal-channel angular extrusion (Segal 1993), which has also been used to produce fine-grained structures, differs from other severe deformation processes in that fairly uniform fine-grained structures (<1 μm) can be generated throughout the cross section of the sample regardless of its dimensions. Thus, bulk samples such as rods and bars, as well as large cast ingots (round or square), can be extruded to produce a homogeneous, fine-grained structure across the whole sample. During this extrusion process, the dimensions of the cross section of the sample remain unchanged; the equivalent deformation is accomplished through a pure shear process while the metal flows through the angle of the container channel. Therefore, relatively low pressure, when compared with conventional extrusion (maximum = yield strength of the material), is required to operate this process. In addition, lower extrusion temperatures are possible for this process. Several studies have been carried out for Al-Li alloys and Ni- and Cu-based alloys (Fedotov and Segal 1983; Segal 1992). The control parameters, such as temperature, pressure, ramming rate, lubrication, and extrusion direction, are important and vary with material. The transition to superplastic deformation of the fine-grained structure in Mg alloys by this process might be used to increase the rate and reduction per pass of conventional extrusion.

Studies should focus on the development of superplastic processes with lower operating temperatures and higher strain rates. Low fabrication cost is a major consideration in increasing the use of Mg alloys in the automotive industry. Low operating temperature, high production rate, and low tooling cost are the key parameters to improving the competitiveness of Mg alloys relative to other materials. Low operating temperatures also decrease the flammability hazards during fabrication.

The effects of SPF on the mechanical properties of nonheat-treatable and heat-treatable Mg alloys should be thoroughly addressed. Microstructural effects during superplastic deformation, including the texture, the size and distribution of second phases, and grain growth and particle coarsening, are important parameters for the understanding of the theoretical basis for superplasticity in Mg alloys. Modeling based on experimental data is important for the design and prediction of the behavior of these materials during and after processing.

Superplasticity in conventional commercial wrought Mg alloys should be addressed. In addition, the feasibility of the diffusion bonding/superplastic forming process (SPF/DB) (ASM 1988) for Mg alloys should be examined. If lightweight materials such as Al and Mg replace conventional steels, their lower stiffness will require thicker structural parts to fulfill design criteria. The stiffness of a structure can be enhanced by honeycomb sandwich construction, which reduces weight while maintaining stiffness. In practice, the fabrication of honeycomb structures is complicated. Joining processing (e.g., welding or adhesive bonding) and extra fasteners are needed; these increase fabrication time and cost. With SPF/DB processing, the fabrication of the honeycomb may be possible in a single operation, because the operating temperature for diffusion bonding is close to that for superplastic deformation. Therefore, the development of this processing method for Mg alloys is desirable for weight reduction and cost effectiveness.

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APPENDIX C:

GLOSSARY

Aging. A change in the properties of certain metals and alloys that occurs at ambient or moderately elevated temperatures after hot working or heat treatment (quench aging in ferrous alloys, natural or artificial aging in ferrous and nonferrous alloys) or after a cold-working operation (strain aging). The change in properties is often, but not always, due to a phase change (precipitation) but never involves a change in chemical composition of the metal or alloy. See also age hardening, artificial aging, natural aging, overaging, precipitation hardening, precipitation heat treatment, progressive aging, quench aging, and strain aging.

Age hardening. Hardening by aging, usually after rapid cooling or cold working.

Artificial aging. Aging above room temperature. See aging and precipitation hardening. Compare with natural aging.

Basal plane. A plane perpendicular to the c, or principal, axis in a tetragonal or hexagonal structure.

β phase. An intermetallic compound formulated as $Mg_{17}Al_{12}$ in Mg-Al alloy systems.

Cathodic protection. Partial or complete protection of a metal from corrosion by making it a cathode, by using either a galvanic or impressed current.

Cold-chamber casting furnace. A die casting machine with an injection system that is charged with liquid metal from a separate furnace.

Creep strength. The constant nominal stress that will cause a specified quantity of creep in a given time at constant temperature or the constant nominal stress that will cause a specified creep rate at constant temperature.

DO_{19}. A hexagonal crystallographic structure with space group $P6_3/mmc$, and Pearson symbol hP2. A common example of a compound with this structure is Ni_3Sn.

Dent resistance. The resistance of materials to indentation. In general, dent resistance increases with an increase in thickness and yield strength of the material.

Ductility. The ability of a material to deform plastically without fracturing, as measured by elongation or reduction of area in a tensile test, by height of cupping in an Erichsen test or by other means.

Elastic constants. Modulus of elasticity. A measure of the rigidity of metal. Ratio of stress, within proportional limit, to corresponding strain. Specifically, the modulus obtained in tension or compression is Young's modulus, stretch modulus or modulus of extensibility; the modulus obtained in torsion or shear is modulus of rigidity, shear modulus or modulus of torsion; the modulus that covers the ratio of the mean normal stress to the change in volume per unit volume is the bulk modulus. The tangent modulus and secant modulus are not restricted within the proportional limit; the former is the slope of the stress-strain curve at a specified point, the latter is the slope of a line from the origin to a specified point on the stress/strain curve. Also called elastic modulus and coefficient of elasticity.

Elastic limit. The maximum stress to which a material may be subjected without any permanent strain remaining upon complete release of stress.

Elastic modulus. Same as modulus of elasticity.

Electrode potential. The potential of a half cell as measured against a standard reference half cell

Eutectic. 1. An isothermal reversible reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling, the number of solids formed being the same as the number of components in the system. 2. An alloy that has the composition indicated by the eutectic point on an equilibrium diagram. 3. An alloy structure of intermixed solid constituents formed by a eutectic reaction.

Fatigue. The phenomenon that leads to fracture under repeated or fluctuating stresses, with a maximum value less than the tensile strength of the material. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of the fluctuating stress.

Fatigue limit. The maximum stress below which a material can presumably endure an infinite number of stress cycles. If the stress is not completely reversed, the value of the mean stress, the minimum stress, or the stress ratio should be stated.

Fatigue strength. The maximum stress that can be sustained for a specified number of cycles without failure, the stress being completely reversed within each cycle unless otherwise stated.

GP zone (Guinier-Preston zone). A small precipitation domain in a supersaturated metallic solid solution. A GP zone has no well-defined crystalline structure of its own and contains an abnormally high concentration of solute atoms. The formation of a GP zone constitutes the first stage of precipitation and is usually accompanied by a change in properties of the solid solution in which they occur.

Galvanic corrosion. Corrosion associated with the current of a galvanic cell that consists of two dissimilar conductors in an electrolyte or two similar conductors in dissimilar electrolytes. Where the two dissimilar metals are in contact, the resulting reaction is referred to as "couple action."

Hardener. An alloy, rich in one or more alloying elements, added to a melt to permit closer composition control than possible by addition of pure metals or to introduce refractory elements not readily alloyed with the base metal. Sometimes called master alloy or rich alloy.

Hot-chamber casting furnace. A die casting machine in which the metal chamber under pressure is immersed in molten metal in a furnace. Sometimes called a gooseneck machine.

Hot shortness. A tendency for some alloys to separate along grain boundaries when stressed or deformed at temperature near the melting point. Hot shortness is caused by low-melting constituents that are segregated at grain boundaries.

Intergranular corrosion. Corrosion that occurs preferentially at grain boundaries.

Latent heat. Thermal energy absorbed or released when a substance undergoes a phase change.

Master alloy. An alloy, rich in one or more desired addition elements, which can be added to a melt to raise the percentage of a desired constituent. See hardener.

Poisson's ratio. The absolute value of the ratio of the transverse strain to the corresponding axial strain, in a body subjected to uniaxial stress; usually applied to elastic conditions.

Precipitation hardening. Hardening caused by the precipitation of a constituent from a supersaturated solid solution. See also age hardening and aging.

Proof stress. 1. The stress that will cause a specified small permanent set in a material. 2. A specified stress to be applied to a member or structure to indicate its ability to withstand service loads.

Reeling. To straighten and planish a round bar by passing it between contoured rolls.

S–N curve. A plot that shows the relationship of stress S and the number of cycle N before failure in a fatigue test.

Solution heat treatment. Heating of an alloy to a suitable temperature, holding at that temperature long enough to cause one or more constituents to enter into solid solution, and then cooling rapidly enough to hold the constituents in solution.

Spinning. Forming a seamless hollow metal part by forcing a rotating blank to conform to a shaped mandrel that rotates concentrically with the blank.

Springback. The elastic recovery of metal after cold forming. The degree to which metal tends to return to its original shape or contour after undergoing a forming operation.

Strain hardening. An increase in hardness and strength caused by plastic deformation at temperatures lower than the recrystallization range.

Stress corrosion cracking. Failure by cracking under combined action of corrosion and stress, either external (applied) or internal (residual). Cracking may be either intergranular or transgranular, depending on the metal and the corrosive medium.

Stress relieving. Heating to a suitable temperature, holding long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses.

Tensile strength. In tensile testing, the ratio of maximum load to original cross-sectional area. Also called ultimate strength.

Twin (Twinning). Two portions of a crystal that have a definite crystallographic relationship; one may be regarded as the parent, the other as the twin. The orientation of the twin is either a mirror image of the orientation of the parent about a "twinning plane" or an orientation that can be derived by rotating the twin portion about a "twinning axis."

Yield strength. The stress at which a material exhibits a specified deviation from proportionality of stress and strain. An offset of 0.2% is used for many metals.

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