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The role of the magnesium industry in protecting the environment

E. Aghion[a,*], B. Bronfin[a], D. Eliezer[b]

[a]Magnesium Research Division, Dead Sea Magnesium Limited, Beer-Sheva, Israel
[b]Department of Materials Engineering, Ben-Gurion University, Beer Sheva, Israel

Abstract

This paper aims at reviewing and evaluating the prospects of magnesium use and applications in the transportation industry that can significantly contribute to the environmental conservation. This relates to the basic characteristics of magnesium being 35% lighter than aluminum, which is used as structural material for vehicles and aerospace applications. The lightness of structural magnesium components results in reducing the weight of transportation means and hence reducing the fuel consumption and CO_2 emissions.

In particular, this paper will introduce the current and future applications of magnesium in the transportation industry with special attention to the needs of alloy developments and advancement in production technologies. © 2001 Published by Elsevier Science B.V.

Keywords: Magnesium; Transportation industry; Casting alloy; Wrought alloy

1. Introduction

Environment conservation depends, to a great extent, on transportation industry, particularly CO_2 emissions produced by road and rail transport vehicles [1]. The European and North American car producers have committed themselves to reduce fuel consumption by 25% and thereby to achieve 30% CO_2 emissions reduction by the year 2010.

There are some possibilities for resolving this problem including such as the use of alternate fuel source, power train enhancements, aerodynamic improvements, etc. However, weight reduction seems to be the best cost-effective option for significant decreasing of fuel consumption and CO_2 emissions [2–5].

Magnesium alloys are the lightest structural material and therefore are very suitable for application in the transportation industry. Magnesium alloy components are usually produced by various casting processes. The most applicable methods are high-pressure die casting and gravity casting, particularly sand and permanent mold casting. Other relevant production technologies are: squeeze casting, thixocasting and thixomolding [6–8].

IMA analysis of magnesium consumption indicates that the use of die-casting magnesium alloys in automotive components continues to grow at an unprecedented annual rate. It means that high-pressure die casting continues to remain the brightest star for magnesium alloys in terms of long-term potential growth [9,10].

While die casting is the dominant form of casting magnesium alloys, low density and other advantages are especially important for heavy components produced by sand casting and mostly operating at elevated temperatures. Special zirconium advantages are especially important for sand cast aerospace applications. Special zirconium containing casting alloys with rare earth elements, yttrium, silver and zinc are used for parts operating at temperatures between 250 and 300°C for extended periods of time [6].

Although cast alloys predominate over wrought products such as extrusions, forgings, sheet and plate, the latter are also being used in a variety of different applications. Recently, a growing interest in the automotive industry in looking at potential applications for magnesium turned back towards wrought alloys. According to the IMA information, magnesium alloy consumption in wrought products increased in 1998 and 1999, reversing the long-term declining trend [10].

This paper aims at reviewing current and future applications of magnesium alloys in the transportation industry including requirements to alloy properties and production technology. Recent achievements in alloy development are also addressed.

2. Magnesium alloys and weight reduction

Magnesium alloys, which are the lightest metallic structural materials offer many possibilities for weight reduction. Triggered by the Corporate Average Fuel Efficiency (CAFE)

* Corresponding author. Fax: +972-7-6472-931.

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Table 1
Magnesium advantages in weight reduction

	Component							
	Engine block		Gear box + clutch housing (Al alloy)	Oil pan (Al alloy)	Four wheels		Engine cradle	
	Cast iron	Al alloy			Steel	Al alloy	Steel	Al alloy
Traditional solution (kg)	32	23.5	21.5 + 5	3	36	23	25	17.5
Magnesium alloy solution (kg)	19		15 + 3	2	18	18	15	15
Weight reduction (kg)	13	4.5	6.5	1	18	5	10	2.5
Weight reduction (%)	40	19	30	33	50	22.5	40	30

Standards and other environmental legislations, most car producers are going to use 40–100 kg of magnesium alloys in the near future [2–5,11].

Table 1 illustrates possible weight reduction replacing steel or aluminum alloys by magnesium alloys for the production of some relatively heavy components. It is evident that using 72 kg of magnesium alloy for components such as engine block, four wheels, gear box housing, engine cradle and oil pan may reduce 48.5 kg in case of steel and aluminum replacement and 19.5 kg in case of substituting for aluminum. In terms of CO_2 emission, it means that substituting for steel in this example will result in fuel saving of 0.25 l per 100 km and in case of substituting for aluminum the fuel saving will be about 0.1 l per 100 km.

Volkswagen AG's philosophy regarding using various production processes for manufacturing different automotive components is illustrated in Fig. 1. It is evident that this company has the intention to use in its vehicles the components produced by various methods including thixocasting and hot metal working processes (extrusion, rolling, forging).

In general, this type of philosophy regarding the use and applications of magnesium alloys can be divided into three stages. The first short-term stage is upgrading the current technologies of available magnesium alloys and casting processes. The second mid-term stage is the developing of special casting technologies such as semi-solid casting and squeeze casting. The third and longest-term stage is the development of wrought alloys technologies in terms of new alloys and new processing methods.

In fact, the development of wrought alloys technologies is the most challenging one as these technologies in magnesium are considered to be extremely underdeveloped. The market situation shows that only 5000 t of wrought alloys are used compared to more than 125 000 t of cast magnesium that are used annually. This situation of magnesium is completely different from the steel and aluminum industries where most of the products are made of wrought alloys.

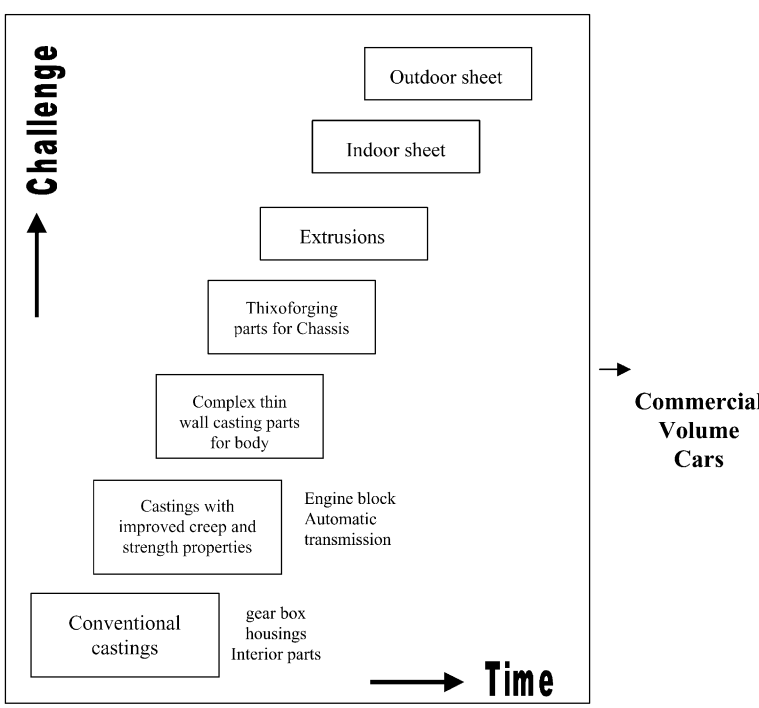

Fig. 1. VW strategy of magnesium technology development [11].

In general, each vehicle consists of four modules: drive train, interior parts, chassis system and body. This paper is reviewing the current and future applications of magnesium alloys in the above groups of components. The requirements for alloys which are under developing and should be developed are also discussed.

3. Magnesium applications in vehicle modules

3.1. Drive train

The list of parts that are currently produced of Mg alloys or potentially could be produced is given in Table 2. Most of these parts are operating at elevated temperatures. Hence, improved creep resistance and stress relaxation properties are critical issues. The poor creep strength of alloys used for manufacturing various housings can result in a clamping load reduction of bolted joints that causes poor bearing-housing contact, leading to oil leak and increased noise and vibration.

Unfortunately, it should be pointed out that no existing die-casting alloy of AZ, AM, AS and AE series [6,7,12] is well suitable for manufacturing drive train parts. This was the reason which stimulated the Magnesium Research Institute (MRI) and Dead Sea Magnesium Ltd. to undertake along with Volkswagen AG, Audi AG and other partners a comprehensive study aiming at the development of creep-resistant die-castable alloy with capability of long-term operation at temperatures up to 150°C under high loads.

The requirements to the new alloy were as follows:

- Die-castability, corrosion resistance, room temperature strength and short-term elevated temperature strength similar to those of AZ91D alloy.
- Creep strength at temperatures of 130–150°C under increased stresses better than that of AE42 alloy.

When developing Mg alloys for die-casting applications, it should be taken into consideration that alloying with Al is strongly recommended in order to provide good fluidity properties (castability). Hence, a magnesium alloy should contain a sufficient amount of Al in the liquid state prior to solidification. On the other hand, the presence of Al leads to the formation of eutectic $Mg_{17}Al_{12}$ intermetallics, which adversely affect creep resistance. Thus, additional alloying elements that can form specific intermetallics with aluminum should be introduced into Mg–Al alloy in order to suppress the formation of β-phase $Mg_{17}Al_{12}$.

Based on this metallurgical consideration and previous experience, various alloy systems were prepared and subjected to detailed examination. Test samples for metallographic examination as well as for tensile and creep testing were produced by direct squeeze casting and high-pressure die-casting processes. Taking into consideration the die-castability properties, creep resistance and mechanical properties, five most promising alloys designated as MRI 151, ..., MRI 155 were selected for upscaled production and further investigation. Table 3 and Fig. 2 illustrate tensile properties and creep behavior of the new alloys at 135°C under a load of 85 MPa, respectively.

3.2. Interior parts

A list of interior parts, which are currently made of magnesium, is shown in Table 1. All of these parts are safety-related components and hence are produced of AM series alloys — AM50A and AM60B. These alloys reveal a good combination of strength, ductility, energy absorption properties and castability. For applications that require higher ductility and toughness, AM20 alloy could be used although this alloy exhibits poor die-castability. Hence, it is a challenge for the magnesium developers to develop a new magnesium alloy, which would combine the strength and castability of AM60B alloy with the ductility and toughness of AM20 alloy.

Another solution can be associated with using vacuum-assisted high-pressure die casting which reduces porosity, and improves ductility and energy absorption properties of conventional alloys such as AM50A and AM60B [5].

3.3. Chassis systems

The list of potential applications of magnesium alloys is given in Table 1. The safety requirements for chassis components represent a challenge for the use of magnesium alloys. Such alloy should combine high ductility and high

Table 2
Current and potential application of magnesium alloys in vehicle parts

Engine and transmission (drive train) parts	Interior parts	Chassis components	Body components
Gear box	Steering wheel cores	Road wheels	Cast components
Intake manifold	Seat components, rear seat	Suspension arms (front and rear)	Inner bolt lid section
Crankcase	Instrument panel	Engine cradle	Cast door inner
Cylinder head cover	Steering column components	Rear support	Cast A/B pillars
Oil pump housing	Brake and clutch pedal brackets		Sheet components
Oil sump	Air bag retainer		Extruded components
Transfer case			
Support			

Table 3
Tensile properties of new alloys (separately die cast test samples)

Alloy	TYS (MPa)	UTS (MPa)	*E* (%)	Impact strength (J)
MRI 151	175 ± 4	277 ± 6	7.5 ± 0.5	7 ± 2
MRI 152	177 ± 3	275 ± 7	6.7 ± 0.4	6 ± 1
MRI 153	168 ± 5	251 ± 6	5.8 ± 0.9	9 ± 4
MRI 154	157 ± 3	251 ± 4	8.5 ± 0.6	11 ± 3
MRI 155	148 ± 3	265 ± 8	12.8 ± 1.6	15 ± 4
AZ91D	167 ± 3	277 ± 6	7.0 ± 0.5	8 ± 2

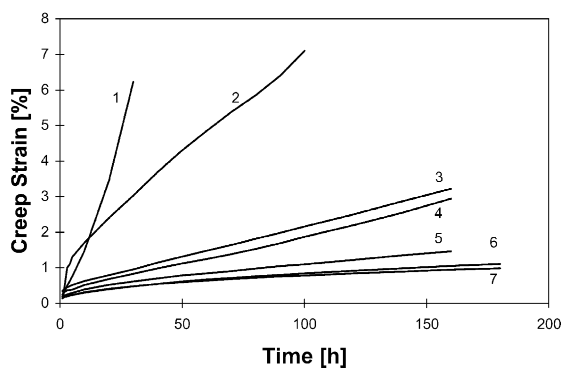

Fig. 2. Creep resistance of new alloys in comparison to AZ91D and AE42 alloy at 135°C under stress of 85 MPa: (1) AZ91; (2) AE42; (3) MRI 155; (4) MRI 153; (5) MRI 154; (6) MRI 151; (7) MRI 152.

strength as well as high fatigue limit under cyclic stress in a corrosive environment.

However, to develop an alloy that exhibits the above combination of properties is very difficult due to the fact that such different properties require different chemical compositions and microstructures. For example, the strength, ductility and toughness are mainly controlled by the bulk microstructure. On the other hand, the corrosion resistance and fatigue strength depend, to a large extent, on the surface layer characteristics.

Another factor in chassis applications is the metal soundness in terms of porosity and inclusions contents that strongly affect the fatigue strength. It is evident that this requirement cannot be satisfied with available alloys like AM60B and AZ91D produced by conventional high-pressure die-casting process. It is believed that other casting processes such as vacuum-assisted HPDC, low-pressure die casting, squeeze casting and thixoforming should be considered as alternative production methods. Additional quality improvement can be achieved by using hot isostatic pressing (HIP) after casting in order to eliminate possible problems with porosity formed due to incomplete filling during the casting process [13].

Another challenging solution may be associated with using wrought alloys in chassis components [14]. It is evident from Fig. 3 that wrought alloys exhibit significantly better combination of strength and ductility compared with casting alloys. Hence, introducing wrought alloys for fabricating various automotive parts can be considered as a substantial breakthrough for magnesium technology.

However, wrought alloys are currently used to a very limited extent due to a lack of suitable alloys and some technological restrictions imposed by the hexagonal crystal structure of magnesium [6]. Thus, summarizing it should be pointed out that more research should be carried out both on alloy development and production technology improvement in order to introduce magnesium alloys into chassis applications.

3.4. Body

The examples of current and potential applications of magnesium alloys in the car's body are given in Table 2. Some of these parts are produced by die casting, others are

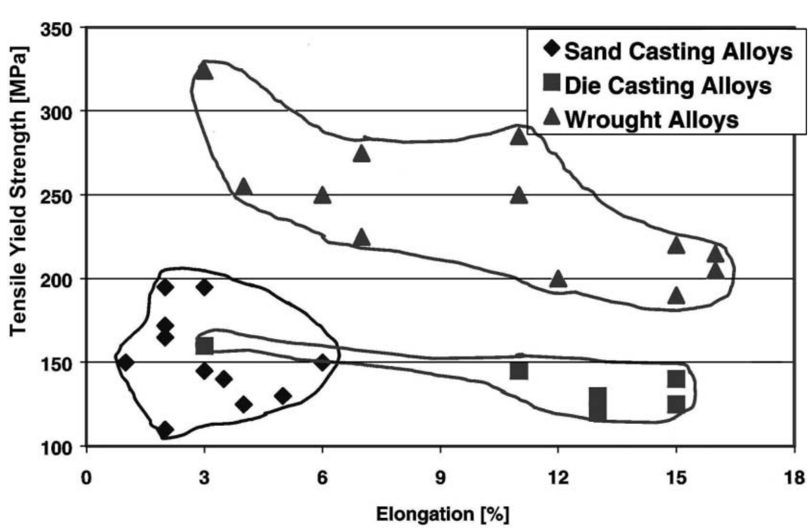

Fig. 3. Tensile yield strength vs. elongation of Mg alloys.

designated to be manufactured by rolling and extrusion techniques.

3.4.1. Castings

The inner boot lid of Volkswagen "Lupo" (TDI 3 l per 100 km car) represents successful application of a complex thin-walled magnesium alloy casting [11]. Other applications, which are going to be introduced in the near future, are door interior components. Both parts require good surface quality and high-energy absorption capability. The existing magnesium alloys such as AM60B and AM50A do not fully comply with the above requirements. Hence, the development of a new alloy with improved properties and ductility in particular is necessary in the future. Another solution is based on the integration of Mg alloy die casting (inside) with Al alloy sheet (outside).

3.4.2. Magnesium alloy sheet and extrusions

It is evident from Fig. 3 that wrought magnesium alloys exhibit significant superior combination of strength and ductility compared to casting alloys. However, existing magnesium alloys, magnesium sheet, for example, do not meet the requirements of outer body panels due to mechanical properties, corrosion resistance and surface quality.

Hence, a new wrought alloy suitable for sheet fabricating should be developed. According to Volkswagen's requirements such alloy should have the capability of being rolled at temperatures not higher than 220°C in order to provide good surface quality. The mechanical properties should be as follows: TYS > 160 MPa, UTS > 250 MPa, $E > 20\%$. The alloy should be available in sheet with width up to 1500 mm.

Magnesium alloy extrusions also exhibit significant better properties than die casting. Conventional Mg alloy extrusions, however, are still inferior to corresponding aluminum alloys in combination of strength, ductility and toughness. Hence, development of new wrought alloys, particularly for extrusion, is a very important challenge for the magnesium industry.

4. Summary

Environment conservation is one of the principal reasons for the focus of attention on magnesium alloys providing vehicle weight reduction and fuel economy. A key to the successful application of magnesium alloys is that designers and engineers need to fully understand how magnesium can assist them to improve vehicle performance and how magnesium alloys relate to other competitive materials.

It is clearly evident that the road for magnesium alloys to become a serious structural competitor in the automotive industry goes through the synergistic effect of alloy development and process development. In particular, the challenge of producing wrought alloy products using conventional technologies such as extrusion, forging and rolling can lead to a breakthrough in the use and application of magnesium alloys in the 21st century.

The current review indicates that most of the future applications are not realistic with the currently available casting and wrought magnesium alloys. Hence, additional fundamental and applied research and development are required in all areas of magnesium technologies and alloy development in order to significantly increase the use of magnesium alloys in various applications.

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