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ORIGINAL ARTICLE

Magnesium and its alloys applications in automotive industry

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Abstract The objective of this study is to review and evaluate the applications of magnesium in the automotive industry that can significantly contribute to greater fuel economy and environmental conservation. In the study, the current advantages, limitations, technological barriers and future prospects of Mg alloys in the automotive industry are given. The usage of magnesium in automotive applications is also assessed for the impact on environmental conservation. Recent developments in coating and alloying of Mg improved the creep and corrosion resistance properties of magnesium alloys for elevated temperature and corrosive environments. The results of the study conclude that reasonable prices and improved properties of Mg and its alloys will lead to massive use of magnesium. Compared to using alternative materials, using Mg alloys results in a 22% to 70% weight reduction. Lastly, the use of magnesium in automotive components is increasing as knowledge of forming processes of Mg alloys increases.

Keywords Magnesium · Mg components · Mg applications · Automotive industry · Transportation · Fuel economy

1 Introduction

Magnesium is the lightest of all the engineering metals, having a density of 1.74 g/cm^3 [1]. It is 35% lighter than aluminium (2.7 g/cm^3) and over four times lighter than steel (7.86 g/cm^3). The physical properties of Mg, Al and Fe are given in Table 1. Magnesium is the eighth most common element. It is produced through either the metallothermic reduction of magnesium oxide with silicon or the electrolysis of magnesium chloride melts from seawater. Each cubic metre of the sea water contains approximately 1.3 kg (0.3%) magnesium [1, 2]. It has a good ductility, better noise and vibration dampening characteristics than aluminium and excellent castability [3]. Alloying magnesium with aluminium, manganese, rare earths, thorium, zinc or zirconium increases the strength to weight ratio making them important materials for applications where weight reduction is important, and where it is imperative to reduce inertial forces. Because of this property, denser material, not only steels, cast iron and copper base alloys, but even aluminium alloys are replaced by magnesium-based alloys [4, 5]. The requirement to reduce the weight of car components as a result of legislation limiting emission has created renewed interest in magnesium [6].

Auto manufacturing companies have made the most of research and development on Mg and its alloys. Volkswagen was the first to apply magnesium in the automotive industry on its Beetle model, which used 22 kg magnesium in each car of this model [7]. Porsche first worked with a magnesium engine in 1928 [8]. Magnesium average usage and projected usage growth per car are given as 3 kg, 20 kg, and 50 kg for 2005, 2010 and 2015, respectively [4, 7]. In the past aluminium and some plastic have been used as the preferred material for some auto parts. In recent years magnesium applications in the auto sector have been increasing [9]. Recent research and development studies of magnesium and magnesium alloys have focused on weight reduction, energy saving and limiting environmental impact [10]. In addition to technical, ecological and economic requirements, basic requirements that are given in Fig. 1 for vehicle components have to be met to achieve these goals [8].

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Table 1 Physical properties of Mg, Al, and Fe [1]

Property	Magnesium	Aluminium	Iron
Crystal structure	hcp	FCC	Bcc
Density at 20°C (g/cm^3)	1.74	2.70	7.86
Coefficient of thermal expansion 20–100°C (×10^6/C)	25.2	23.6	11.7
Elastic modulus [Young's modulus of elasticity] (10^6 Mpa)	44.126	68.947	206.842
Tensile strength (Mpa)	240 (for AZ91D)	320 (for A380)	350
Melting point (°C)	650	660	1.536

Global trends force the automotive industry to manufacture lighter, more environmentally friendly, safer and cheaper cars [4]. The leading automakers are concentrating on the reduction of car weight and limiting the amount of exhaust emissions due to legislative and consumers' requirements for safer, cleaner vehicles [7]. As CO_2 emission is in direct proportion to fuel consumption, car weight has become the most critical criterion of design efficiency assessments [11]. Weight reduction not only saves energy but it also reduces greenhouse gas emissions. Reducing the automotive weights by a certain amount will result in a similar percentage of improvement in fuel economy as seen in Fig. 2. Fuel efficiency leads to extensive evaluation of the potential use of magnesium components. Weight reduction of 100 kilograms represents a fuel saving of about 0.5 litres per 100 kilometres for a vehicle [12]. High-strength steels, aluminium (Al) and composites are already being used to reduce weight, but additional reductions could be achieved by greater use of low-density magnesium and its alloys. Reduction in weight can be obtained by a combination of innovative structural design and increased use of lightweight materials [13, 14]. Currently, the average vehicle in North America uses 0.25 % (3.8 kg) magnesium and 8% (120 kg) aluminium [15]. Significant research is still needed on magnesium processing, alloy development, joining, surface treatment, corrosion resistance and mechanical properties improvement.

Environmental conservation is one of the principal reasons for the focus of attention on Mg and its alloys. Environment conservation depends, to a great extent, on transportation industry, particularly CO_2 emissions produced by transport vehicles [16]. Weight reduction is the most cost effective option for significantly decreasing of fuel consumption and CO_2 emissions [9, 16]. European and North American car producers have planned to reduce fuel consumption by 25%, thereby achieving a 30% CO_2 emission reduction by the year 2010 [9, 16, 17]. The consumption of magnesium has shown a broad increase in the last 20 years. North America is the main consumer followed by the Western Europe and Japan [4, 18]. Most of the available magnesium is still used for alloying aluminium and only about 34% is directly used for magnesium parts, which can be divided into casting applications (33.5%) and wrought materials (0.5%) [4, 19].

A lightweight part made of magnesium on a car may cost more than that of aluminium, but Mg cost compensates for Al cost due to reduction in fuel and CO_2 emission [17]. High cost is a major obstacle to greatly increased magnesium use in the automotive industry. The cost of the finished product must be competitive. However, magnesium has struggled for acceptance for many years, mainly due to a high price when compared to aluminium [20]. The wide variation of price is being overcome as seen in Fig. 3 and magnesium is now ready to be more widely used to benefit for industrial applications and environment [1, 7, 8, 16, 17, 20]. The European Union adopted a new strategy to reduce carbon dioxide emissions from new cars and vans sold in the European Union [21]. This new strategy underline the Commission's determination to

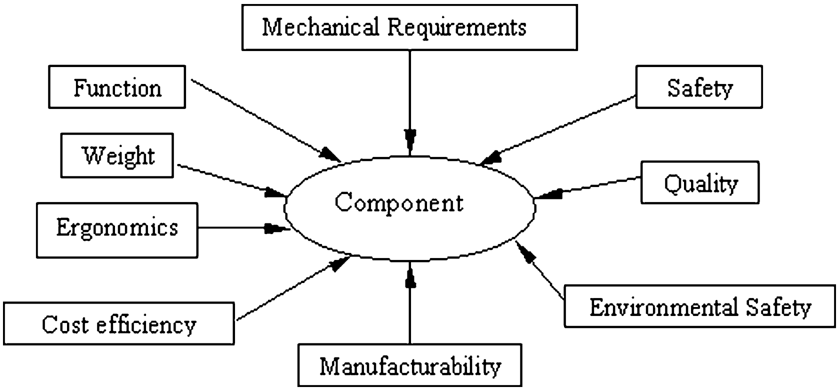


Fig. 1 Basic requirements for vehicle components [1]

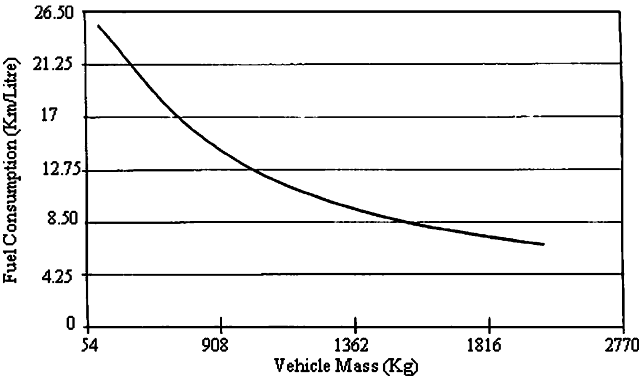


Fig. 2 The relation between vehicle mass and fuel consumption [5]

ensure the EU meets its greenhouse gas emission targets under the Kyoto Protocol [22] and beyond. The strategy will enable the EU to reach its long-established objective of limiting average CO_2 emissions from new cars to 120 grams per km by 2012-a reduction of around 25% from current levels.

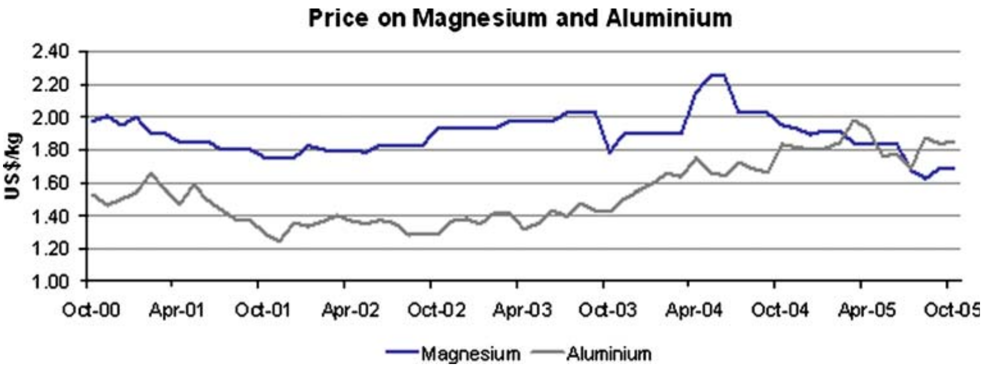
The cost of magnesium alloys has decreased below the aluminium per kg since 2004 as seen in Fig. 3 [23]. Magnesium also has other basic inherent advantages, such as greater rigidity and higher damping capacity [20]. Magnesium alloys lower fabrication joining costs, substitution by lightweight materials enable secondary weight savings, and lifetime fuel costs are reduced, and the total lifecycle cost of a Mg part is lower than that of one made from other materials [15, 24–26]. Developing new alloys which have better formability could enable major cost reduction. In addition to a per-pound basis, magnesium costs were more than the cost of aluminium until 2004, whereas on a volume basis the prices of both were approximately the same. These reasonable prices for Mg will spur the massive use of Mg in automotive industry.

In this paper, the science, technology and applications of magnesium and its alloys in the automotive industry that can significantly contribute to the fuel economy and environmental conservation are reviewed in the wake of new developments. The current advantages, limitations, technological barriers and future projection of usage of Mg alloys in automotive industry are also given.

2 Mechanical properties of Mg alloys

Specific strength and specific stiffness of materials and structures are important for the design of weight saving components. Weight saving is particularly important for automotive bodies, components and other products where energy consumption and power limitations are a major concern [27]. The specific strength and specific stiffness of magnesium are compared with aluminium and iron in Fig. 4. There is little difference between the specific stiffness between Mg, Al and Fe as seen in Fig. 4. The specific stiffness of Al and Fe is higher than Mg only in the ratio of 0.69% and 3.752%, respectively. On the other hand, the specific strength of Mg is considerably higher than that of Al and Fe in the ratio of 14.075% and 67.716%, respectively, as seen from the figure. New magnesium alloys are needed to meet the automobile component requirements for elevated temperature strength and creep resistance. Grain boundary sliding has been observed to be the main creep mechanism in magnesium alloys in the stress-temperature ranges of interest for automotive application [28]. Magnesium seems to creep even at low temperature by a stress-recovery mechanism. The creep mechanism at low temperature is basal slip within the grains and sub-grains formation while at higher temperatures the diffusion-dependent mechanism becomes predominant [29]. Mg-Al alloys are one major group among magnesium-based alloys. The strength of these alloys is improved by forming a solid solution where 11.5 atomic percent Al are soluble in the Mg matrix at 437°C [30, 31]. The microstructure of these alloys is characterised by the Mg-g (Mg 17 Al 12) eutectic at the grain boundaries. In addition to this poor coherency, if Mg-Al alloys are exposed to elevated temperatures (>150°C) for long periods of time, the supersaturated Mg solid solution transforms to Mg matrix with coarsely dispersed Al (g) precipitates and contributes to grain boundary migration and creep deformation. Furthermore Al (g) is also prone to aging and has poor metallurgical stability, which limited its application in higher temperatures [30, 31]. Early developments in improving the creep properties of magnesium were made

Fig. 3 Changes in the prices of magnesium and aluminium [20]



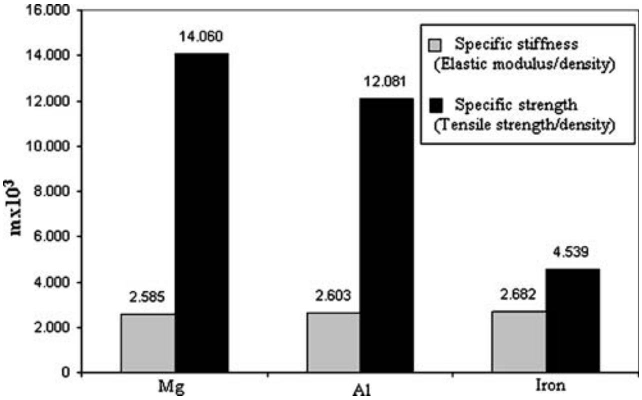


Fig. 4 Comparison of basic structural properties of magnesium with Al and iron

in the 1960s by Volkswagen [12]. It was based on Mg-Al-Si system. These alloys exhibit marginally improved creep resistance but are difficult to die-cast. Magnesium components are generally in the form of magnesium alloys. The addition of other alloying elements can strengthen and harden magnesium as well as alter its chemical reactivity. The common magnesium alloys are shown in Table 2. AZ91D magnesium alloy has been shown to creep at ambient temperature under initial applied stress of only 39% of its yield stress [32]. The commonly used die-casting alloy AZ91, starts creep at temperatures above 100°C and has a maximum operating temperature at 125°C [17]. Because of its creep behaviour, it is not convenient to use this alloy for power train and engine castings. Both of them operate at temperatures of 100°C or more and are fixed together with threaded fasteners so creep becomes a key issue for these applications [31]. The studies on AE42 alloy showed that AE42 has a greater percentage of initial compressive load than AZ91D [30, 31] as seen in Fig. 5. AE series alloys have better creep resistance with respect to AZ91D. Magnesium alloys for automotive applications must have good creep resistance property. These alloys should be thermally and metallurgically stable and resistance to flow during creep loading. Moreover, it should have adequate corrosion resistance, castability and strength [15, 29–31]. The AE42 (Mg-4 atomic percent Al-2 atomic percent rare earths) magnesium alloy has improved creep resistance over the other alloys as seen in Fig. 5. Magnesium-thorium alloys display excellent creep properties at elevated temperature (350°C). However, these alloys have cast disadvantages due to expensive rare earth additions [28, 31]. The Mg-Al-Sr system is a recently developed alloy for the heat-resistant lightweight Mg alloys. The Mg-Al-Sr system is used by BMW for the manufacturing of die-cast engine blocks [33]. This system has excellent mechanical properties, good corrosion resistance and excellent castability. Mg alloys with Sr addition have better creep resistance than other alloy systems as seen in Fig. 5. Tensile of the Mg-Al-Sr system at 150°C was superior to

Table 2 Common magnesium alloys and their applications [1, 2, 7, 28–31, 41, 42]

Alloy designation	Alloying additives	Uses	Basic properties and applications
AZ91	9.0% Al, 0.7%Zn 0.13%Mn	General casting alloy	Good castability, good mechanical properties at T<150°C
AM60	6.0% Al, 0.15%Mn	High pressure die-casting alloy	Greater toughness and ductility than AZ91, slightly lower strength. Often preferred for automotive structural applications
AM 50	Mg-Al system	General casting alloy	Good strength, ductility, energy absorption properties and castability
AE44	Mg-Al-rare earth system	General casting alloy	Better creep behaviour and castability than AE42
AE42	Mg-4 atomic percent Al-2 atomic percent rare earths	General casting alloy	Low castability, good creep behaviour
AS41	4.2%Al, 1.0%Si	General casting alloy	Better creep resistance than AZ91 at elevated temperatures but lower strength
ZE41	4.2%Zn, 1.2%RE, 0.7% Zr	Specialist casting alloy	Rare earth addition improves creep strength at elevated temperatures. Pressure tight.
AZ31	3.0% Al, 1.0Zn, 0.2% Mn	Wrought magnesium products	Good extrusion alloy
AM20	Mg-Al system	Casting alloy	High ductility, toughness, poor die-castability
MRI 153M	Mg-Al-Ca-Sr System	Casting alloy	For high temperature applications up to 150°
MRI 230D	Mg-Al-Ca-Sr System	Casting alloy	For high temperature applications up to190°
AS 21	Mg-Al-Si system	Casting alloy	For use at temperatures in excess of 120°C
AJ62	Mg-Al-Sr system	High pressure die-casting (HPDC)	Good thermal and mechanical strength, superior castability, corrosion resistance and creep behaviour

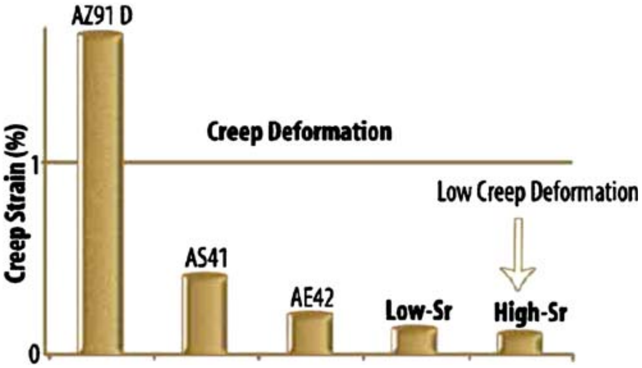


Fig. 5 Comparison at creep deformation of die-cast Mg-alloys (35 MPa, 150°C, 200 h) [31]

AE42 as seen from Fig. 5. Corrosion resistance of the Mg-Al-Sr alloys is similar to AZ91D and better than AE42, which indicates that strontium does not have adverse affect on corrosion properties [12]. Figure 6 illustrates the tensile properties and creep behaviour of the new alloys at 135°C under a load of 85 MPa respectively [17]. The addition of Al to Mg alloys provide good fluidity leads to the formation of eutectic $Mg_{17}Al_{12}$ intermetallics which adversely effect creep resistance as seen in Fig. 6. Wrought alloys exhibit significantly better combination of strength and ductility compared with casting alloys. 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 [5].

3 Recent processing applications of magnesium alloys

Significant research is still needed on magnesium processing, alloy development, joining, surface treatment, corrosion resistance, and mechanical properties improvement.

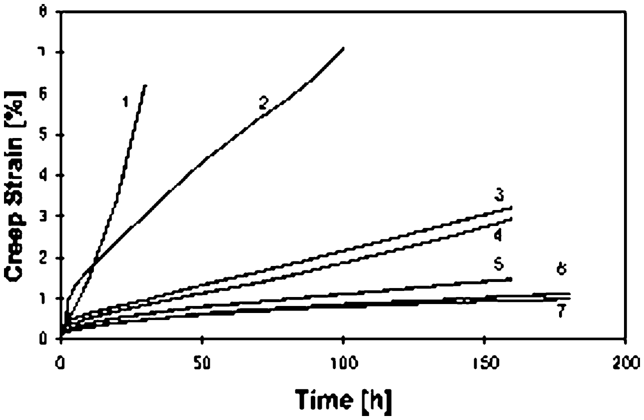


Fig. 6 Creep resistance of new alloys in comparison to AZ91 and AE42 alloy at 135°C under stress of 85 MPa : (1) AZ91; (2) AE42; (3) MRI 155; (4) MRI 153; (5) MRI 154; (6) MRI 151; (7) MRI 152 [17]

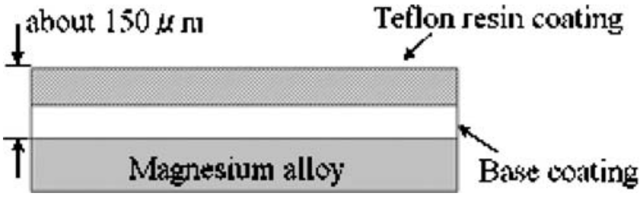


Fig. 7 Schematic view of the cross-section for Teflon resin coating [34]

3.1 Coating

Different coating methods are used to increase the corrosion resistance of magnesium alloys. Problems with contact corrosion can be minimized, on the one hand, by constructive measures and, on the other hand, by an appropriate choice of material couple or the use of protective coatings [4, 18]. Surface coatings produced for magnesium die-casting by hexavalent chromium baths have been used to provide stand-alone protection and as a pre-treatment for painting. These baths are not considered to be environmentally friendly. New alternative coating methods are being investigated as seen in Fig. 7. Chromate coating of Mg alloys is hazardous and not environmentally friendly. A newly developed Teflon resin coating has been developed for Mg alloys [34]. The coating is obtained with an aluminium vapour deposition and finish treatment with a Teflon resin coating as seen in Fig. 7. The newly developed Teflon resin coating is a low cost, chromium-free corrosion-resistant coating for magnesium alloys. The coating not only has corrosion resistant properties, but also good lubricity, high frictional-resistance and non-wetting properties. The main future of the coating is in the application of Teflon coating on magnesium alloys (Fig. 7). “Al coating” is also used for magnesium alloys using aluminium vapour deposition and finish treatment by resin coating. The Al coating provides high corrosion resistance for magnesium alloys with various metallic lusters. On the other hand, Teflon resin coating provides some corrosion-resistance properties at a lower cost with good lubricating properties, compared with “Al Coating”. Teflon resin coating will enhance the potential applications of magnesium alloys for automotive industry [34]. Iron phosphate-based coatings are developed for Mg alloys.

3.2 Alloying

Because of its too low mechanical strength, pure magnesium must be alloyed with other elements, which confer improved properties. The Mg-Al-Zn group of alloys contains aluminium, manganese, and zinc. These are most common alloying elements for room temperature applications. Thorium, Cerium, and Zirconium (without aluminium) are used for elevated temperatures and form the Mg-Zn-Zr group [35]. Thorium or cerium is added to improve strength at the temperatures of 260°C to 370°C. Aluminium is the most effective ingredient in improving results. As little as 2% to 10% aluminium with minor additions of zinc and manganese increases strength and hardness, at the expense of less ductility, without impairing weldability and making the alloy responsive to heat treatment. Magnesium alloys containing more than 1.5% Al are susceptible to stress corrosion and must be stress relieved after welding. Iron, copper and nickel are considered impurities to be limited because they degrade the corrosion resistance of magnesium alloys. Zinc combined with aluminium overcomes harmful corrosive effects of iron and nickel impurities that may be present in magnesium alloys. The higher the Zn content (over 1%) the higher the hot shortness, causing weld cracking [4, 35]. Manganese improves yield strength and the saltwater resistance of magnesium alloys.

3.3 Joining

Rivetting or any of the commonly used welding methods can be used to join magnesium. Screw joints are used by Mg alloys. Screw joints cause no problems if the property profile of magnesium alloys is considered for dimensioning and designing of the joint. Different coefficient thermal expansion can cause loss of pre-stress due to creep of the Mg parts at temperatures above 100°C if steel bolts are used. For use at elevated temperatures, it is better to replace the steel by aluminium bolts. Mg extrusions / Mg sheets and pore-free magnesium casting can be joined using the automated gas metal arc welding (MIG), gas tungsten arc welding (TIG), Nd:YAG laser welding, electron beam welding and solid state welding [4, 5, 35, 36]. The relative weldability of the different magnesium alloys is similar to that for the more common arc processes [37]. Shielding the welding region by inert gas or flux is needed to prevent the fire hazard/risk. The used shielding gas is generally argon and mixtures with helium are also acceptable [4]. Grain growth adjacent to the weld reduces strength. Zirconium in small amounts is a grain refiner that improves weldability. Beryllium is sometimes added to reduce the tendency of magnesium to burn while melting. Calcium is added in small amounts to reduce oxidation, but increase the risk of weld cracking [4, 18]. Wrought alloys are usually welded more easily than certain cast alloys. One of the most common welding magnesium applications is the repair of casting either as cast or after service [4, 35]. Preheating is needed in welding-magnesium applications because of the degree of joint restraint and metal thickness. Preheating should be performed in a furnace with protective atmosphere for reducing oxidation [38]. Stress relieving is generally needed, after substantial repair welding of casting. Electron beam welding of magnesium has been used for repair of expensive castings where feasible, on alloys containing less than 1% zinc. The conditions have to be strictly monitored because of the danger of developing voids and porosity due to the low boiling point of magnesium. A slight defocused beam may help in obtaining sound welds [37]. A laser beam is a preferred method for welding magnesium because of low heat input, elevated speed and limited deformation; however, the tendency of developing porosity must be considered. Resistance welding of magnesium, either spot or seam, is performed on wrought alloys like sheet and extrusions, essentially with equipment and conditions similar to those used for aluminium [35, 37, 38]. In all cases the surface should be thoroughly degreased and, if present, the chrome-pickling protective coating should be locally removed before welding. Oxyacetylene welding procedure is not recommended for magnesium because it requires complex flux neutralization procedures [4]. Recently developed friction stir welding is the best process for the welding of Mg alloy in the cases that it is possible to use FSW process. Problems in fusion welding of magnesium alloys such as solidification cracking, liquation cracking and porosity are eliminated with FSW due to its solid state nature of process [39].

3.4 Casting

Magnesium alloy components are usually produced by various casting processes. Contraction of Mg from liquid to solid is 3.9% to 4.2% and from liquid at melting temperature to a solid at room temperature is 9.7% [40, 41]. The widely used methods are high-pressure die-casting and gravity casting, particularly sand and permanent mold casting. The following are other relevant production technologies: squeeze casting, thixo-casting and thixomolding [42]. 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 [12, 28, 30, 31, 33]. Die-casting is one of the most effective fabrication methods to produce magnesium components in automotive industry. However, the number of available Mg-based alloys for die-casting is very limited. AZ91 is the principle alloy which represent 80% of magnesium casting components for applications over 95°C such as power train components in automobile applications because of their restricted creep properties which limited the current application of magnesium to non-critical part such as valve covers [12]. Die-casting of Mg alloys reduces the total part weight, vibration and noise, while improving dimensional accuracy and repeatability. Die-casting of magnesium alloys results in better elongation and longer die life than aluminium die-casting. High cost is a major obstacle to greatly increased magnesium use in automotive industry [15]. Developing new alloys, which have better formability, could enable major cost reduction.

3.5 Forming

Forming behaviour of magnesium is poor at room temperature, but most conventional processes can be performed when the material is heated to temperatures between 230°C to 370°C [4, 12]. Formed and drawn magnesium products are manufactured at this temperature ranges generally without a protective atmosphere. Wrought alloys generally have higher strength and ductility in comparison with cast alloys. The hexagonal structure of magnesium requires elevated forming temperatures to activate more slip systems and to allow better formability, causing higher energy consumption during processing and causes also a poorer surface appearance [1, 8]. Surface quality and corrosion requirements of the present magnesium sheet alloys are not sufficient for other panel applications. Therefore, additional process developments are needed to solve this problem. AZ31 sheet products are available on the world market in a thickness of 0.8-30 mm and widths at up to 1850 mm [5]. AZ31 sheet as magnesium has similar hot deep-drawing characteristics as steel and aluminium sheet [4]. At 225°C the draw ratio of AZ31 is 2.6 and is higher than that of deep drawing Al and deep drawing steels in common use which have a ratio of 2.5 and 2.2, respectively [12]. Further investigation is needed for bending and hydroforming. Minimum wall thickness of Mg alloys is approximately 1.5 mm for extruded magnesium components, depending on the section's geometry [41]. The potential application of magnesium profiles strongly depends on the question whether established forming processes for aluminium and steel can be easily adopted to magnesium [9, 4, 12, 43].

4 Present technological barriers and solutions for magnesium alloy applications in automotive industry

The disadvantages of Mg alloys are high reactivity in the molten state, inferior fatigue and creep compared to aluminium and galvanic corrosion resistance. The problems in using magnesium alloys stem from their low melting points 650°C and their reactivity (inadequate corrosion resistance) [44]. The main problem for Mg alloys encountered during fabrication and usage is the fire hazard/risk, especially in machining and grinding processes due to their relatively low melting point [45]. In roughing cuts the chips are generally thick and not likely to get hot enough to ignite. However, the thin chips produced in the finishing cuts are more likely to heat up and ignite. Similarly, the dust in grinding can ignite, even explode, if heated to melting temperatures. The fire hazard / risk can be eliminated by avoiding fine cuts, dull tools, high speeds; using proper tool design to avoid heat build up; avoiding the accumulation of chips and dust on machines and cloths; and using coolants. Water-based coolants cannot be used with Mg alloys, since they reduce the salvage value of the scrap and increase the risk of fire [46].

The reaction of the Mg with water:

$$Mg + H_{2O} \rightarrow MgO + H_2 \qquad (1)$$

Oxide formation reduces the salvage value, and the hydrogen increases the fire risk. Another possibility is the hydroxide reaction:

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 \qquad (2)$$

Magnesium hydroxide [$Mg(OH)_2$] can form at ambient temperature in water/moisture-containing chlorine or sulphur atoms. The salts destroy the passive layer, leading to an acceleration of general corrosion and pitting rates [46]. Magnesium hydroxides tend to react with the environment and transform to more stable compounds, such as carbonates (hydrated or basic) or sulphates of magnesium. Conversion of magnesium to compounds lowers the salvage value of the scrap and the generated hydrogen increases the fire risk [45]. A fire hazard/ risk can also exist during heat treatment if the solution heat treatment temperatures of certain alloys are exceeded. After solution treatment, magnesium alloys are quenched in forced or still air. Occasionally a water quench is used to develop desired properties in certain alloys, especially in thicker gage products. Oil or glycol quenches can develop similar properties [47]. An increase in alloy content depresses the melting point, enlarges melting range and increases weld cracking tendency of magnesium alloys. High alloy content needs less heat for melting and also limit grain growth, showing higher welding magnesium efficiency [47].

Another problem of magnesium alloys is reactivity [44]. Magnesium is a reactive metal, so it is not found in the metallic state in nature. It is usually found in nature in the form of oxide, carbonate or silicate often in combination with calcium [1]. Because of this reactivity the production of magnesium metal requires large amounts of energy [47]. This situation makes magnesium an expensive metal. There are two mechanisms of reactivity of magnesium alloys [46]. In the first mechanism, magnesium alloys can react with oxygen and form oxides and with water/moisture even at ambient temperatures, they lead to an increased risk of fire. In the second mechanism, magnesium alloys are at the bottom of the galvanic series (-1,60 volt Electro-motive Force-EMF) [47]. An EMF difference of 0,20 Volt or more activate galvanic action [46, 47]. Magnesium alloys will form active galvanic couples, acting as corroding anodes, with other metallic components in their proximity. To prevent reactivity problems, protective finishes, such as anodic coating or paint are used [48]. Chemically applied coatings e.g. chromate conversion coatings only supply

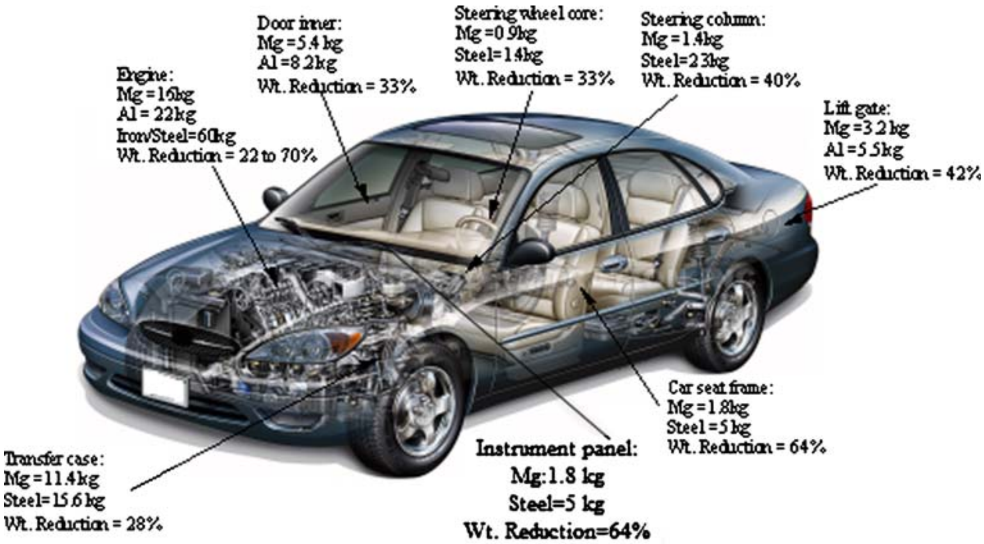


Fig. 8 Some automotive components made of Mg alloy and obtained weight reduction

limited term protection and are water-soluble. These coatings should be used in conjunction with paint schemes. Design of the parts is important for adequate drainage, to prevent the accumulation of corrosive substances, such as water/moisture [49].

Flammability, magnesium does not burn unless it melts. Fine magnesium powder and chips created in machining operations can cause fire. Magnesium is highly oxidizable. In the form of machined chips or powders, there is the risk of burning of chips or powders, if ignited, with dangerous intensity. The machining process of the components must be performed under controlled conditions, with extinguishing agents ready on the spot [45]. Magnesium is attacked by inorganic acids. It is not attacked by alkalis and caustic soda. Welding of Mg alloys can also present a fire risk if the hot/molten metal comes in contact with air. To

Table 3 Producers of Mg alloy component and applications on car models [52]

Component	Producers and car models
Engine block	BMW: lighter, more powerful and durable six-cylinder inline combustion engine. The world's first engine block made of Noranda's patented alloy AJ62 (Mg-Al-Sr).
Steering wheel frame	Ford *(Ford Thunderbird, Cougar, Taurus, Sable),* Chrysler *(Chrysler Plymouth)*, Toyota, BMW *(MINI),* Lexus *(Lexus LS430).*
Seat frame	GM *(Impact),* Mercedes-Benz *(Mercedes Roadster 300/400/500 SL),* Lexus *(Lexus LS430)*
Instrument panel	GM, Chrysler *(jeep),* Ford, Audi *(A8),* Toyota *(Toyota Century)*
Wheel rims	Toyota *(Toyota 2000GT, Toyota Supra),* Alfa Romeo *(GTV),* Porsche AG *(911 Serie)*
Cylinder head	Dodge *(Dodge Raw),* Honda Motor *(City Turbo),* Alfa Romeo *(GTV),* AutoZAZ-Daewoo *(Tavria, Slavuta, Daewoo-Sens),* Honda, BMW, Ford, Isuzu, Volvo Motors *(LCP),* Chrysler
Clutch case	AutoZAZ-Daewoo *(Tavria, Slavuta, Daewoo-Sens),* Volvo Motors *(LCP),* Alfa Romeo *(GTV)*
Transmission case	AutoZAZ-Daewoo *(Tavria, Slavuta, Daewoo-Sens),* Volvo Motors *(LCP),* Porsche AG *(911 Serie),* Volkswagen *(Volkswagen Passat),* Audi *(A4,A6),* Mercedes-Benz
Lower crankcase	Chrysler *(jeep),* Alfa Romeo *(GTV),* GM *(Oldsmobile),* McLaren Motors *(F1-V12)*
Cylinder block (without liners and main bearing heads)	GM *(Pontiac Gran AM, Corvette)*
Intake manifold	GM *(V8 North Star motor),* Chrysler
Air intake system	BMW *(V8 motor)*
Steering link bracing	GM *(LH Midsize)*
Oil pump body	McLaren Motors *(F1-V12)*
Camshaft drive chain case	Porsche AG *(911 Serie)*
Gear controls housing	AutoZAZ-Daewoo*(Tavria, Slavuta, Daewoo-Sens)*
Brackets for air comfort system compressor, steering booster pump and generator	Chrysler, Volkswagen (Volkswagen Lupo)

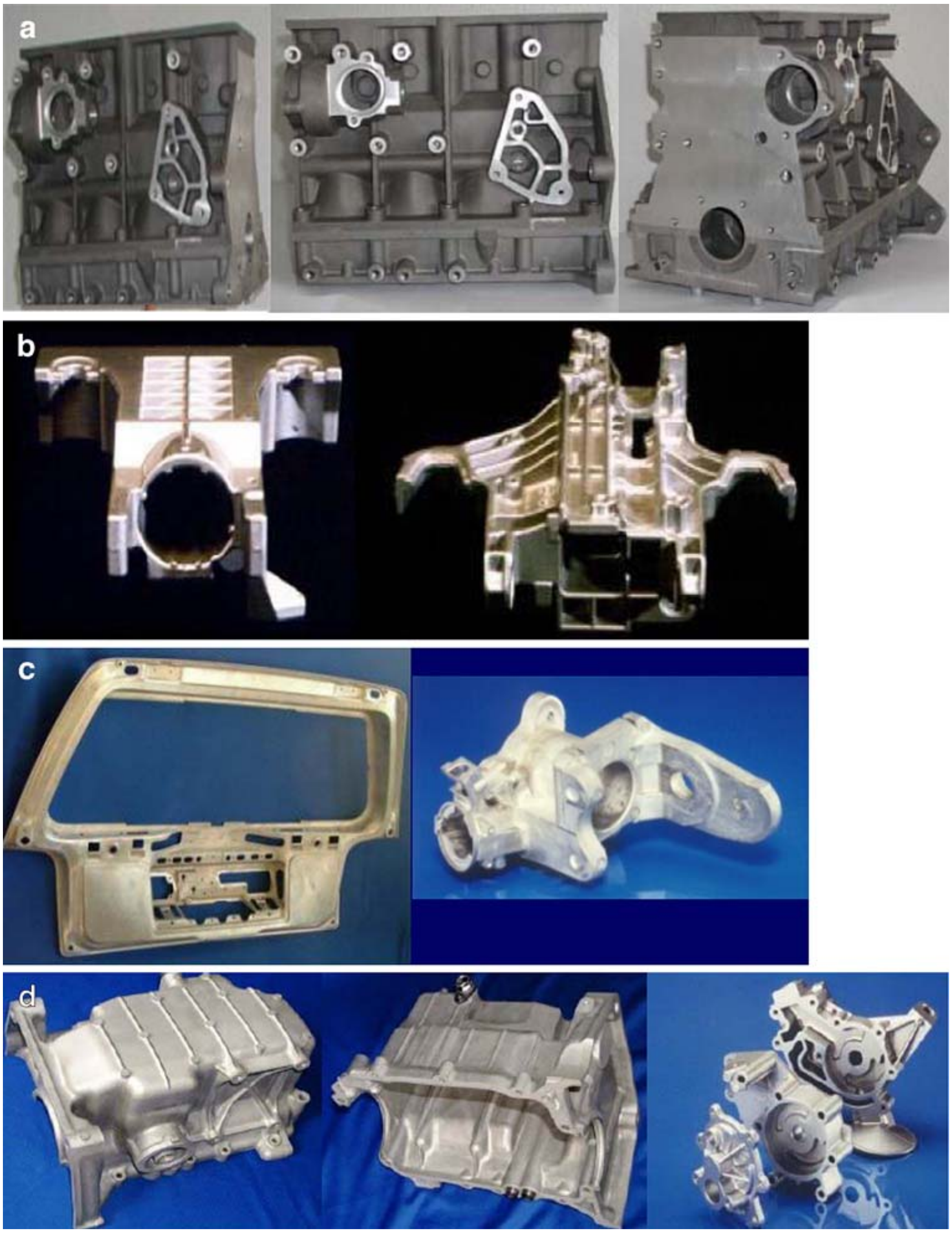


Fig. 9 Examples of automotive components made of Mg alloys (**a**: Engine block, **b**: Steering column module, **c**: Door frame / Key lock housing, **d**: Oil pan, **e**: Steering wheel, **f**: Transfer case/Transmission housing, **g**: Seat frame, **h**: Wheel)

overcome this problem, the welding region must be shielded by inert gas or flux. A larger amount of distortion relative to other metals may arise due to high thermal conductivity and coefficient of thermal expansion in welding of magnesium alloys if required precautions are not taken [35]. Service temperatures must be well below the alloy melting points; otherwise the fire hazard might materialize. For example, it caused an engine fire in a DC-3 aircraft, resulting in a fatal crash [47]. This particular aircraft was built during World War II, when aluminium shortages forced manufacturers to use of magnesium alloys as a replacement in some applications [47].

The low creep properties of magnesium alloys limits the application of magnesium alloys to be used for critical parts, such as valve covers [4, 5, 8, 12]. The following are the main issues that need attention to increase creep properties of magnesium alloys: stress relaxation in bolted joints, the potential for creep at only moderately elevated temperatures, corrosion resistance, and the effects of recycled metal on properties. Magnesium has higher oxygen potential than most metals. The oxidation of molten magnesium has a continuance characteristic and accelerates [1]. Thus, melting must be carried out under a controlled atmosphere. Magnesium alloy may contain more inclusions than aluminium alloys if the

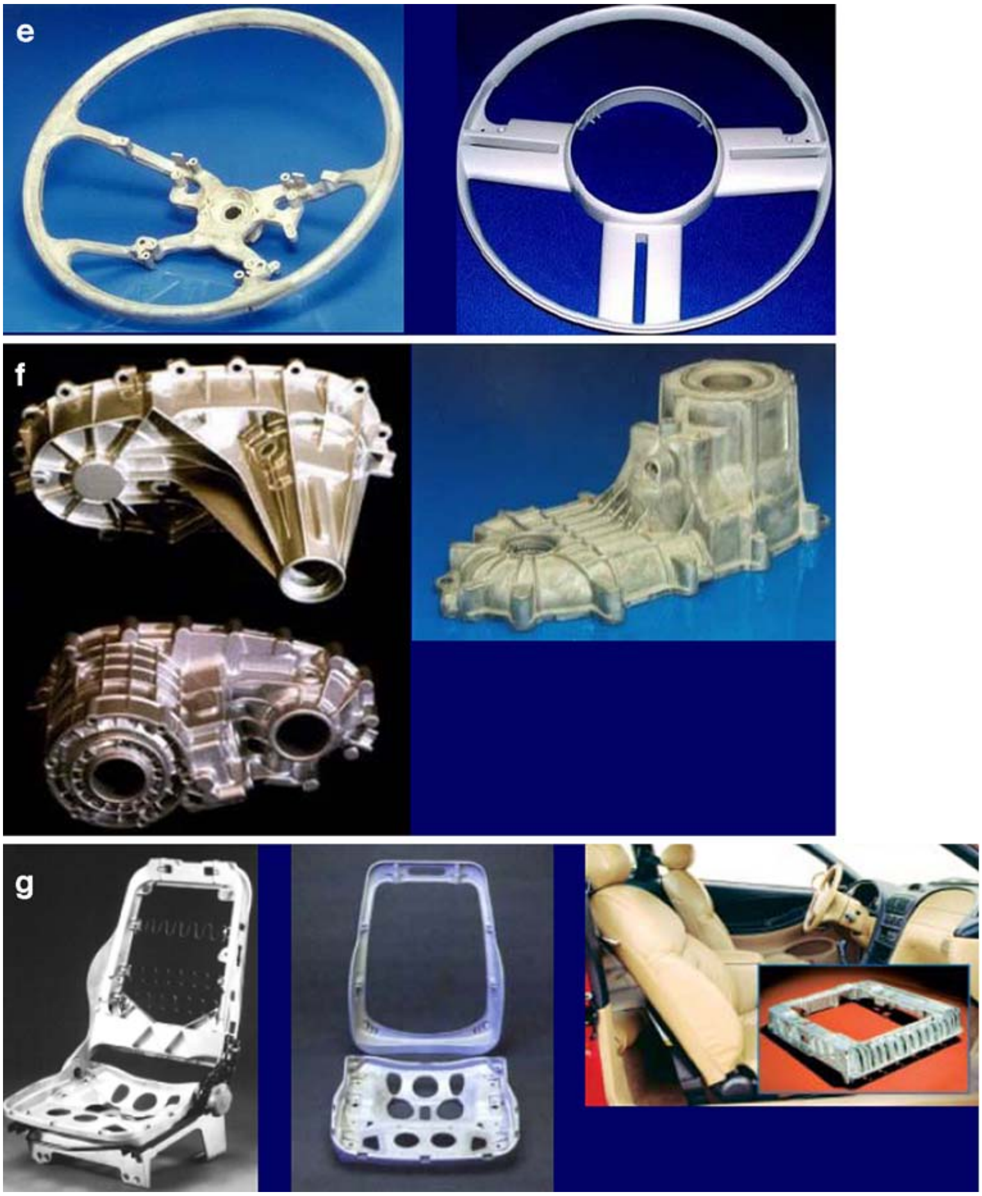


Fig. 9 (continued)

required precautions are not taken during melt treatment and refining processes [42]. The impurities in molten magnesium do not naturally tend to float to the surface. The tested method to overcome this problem includes sparging the molten metal with argon, which brings dross to the surface that can than be skimmed off. The molten metal is pumped to ingot molds through a 410 grade stainless steel filter which removes larger particles [1, 42].

Magnesium tends to corrode faster than other materials. To overcome this problem, development in design, assembly research, and coatings is needed. The electrode potential of magnesium places it high in the electrochemical series. Problems also occur with galvanic corrosion requiring protection when there is contact with other metals; however, good design and appropriate protection concepts can alleviate these concerns [50]. Magnesium alloys has good corrosion resistance in the atmospheric conditions, but their susceptibility to corrosion in chloride environments has been a serious practical limitation to wider application of these alloys. Magnesium is at the active end of galvanic series; thus, galvanic corrosion is an ever existing threat [1]. In spite of these limitations, significant improvements have been made with magnesium alloys in the corrosion resistance by reducing the heavy metal impurity level (Fe, Ni and Cu) [27–33]. In the molten state, magnesium alloys react with oxygen in the air. During the magnesium melting and refining process, the molten metal surface must be protected to prevent oxidation. Various fluxes, sulphur, sulphur dioxide or sulphur hexafluoride are used for this purpose [51].

Fig. 9 (continued)

5 Mg alloy applications in automotive industry

Assuming 20 kg of magnesium alloy components will be used instead of alternatives on 25% of the 40 million cars produced, one calculates that the car manufacturing industry requires 200,000 tons of magnesium alloys. Therefore, a 50% increase in the total world production of magnesium is needed. Magnesium alloys that will withstand higher temperatures are being developed for engine blocks and transmission housings. BMW manufactured a composite magnesium-aluminium alloy engine, the R6, that is the lightest 3.0 litre in-line six-cylinder gasoline engine in the world [33]. The company reports that the most important aspect of choosing magnesium for this radically advanced engine concept is the significant weight reduction. BMW's goal was to achieve an engine capable of increased power output and higher torque, while still lowering fuel consumption and CO_2 emissions. From 1990 to 2007, BMW reduced the fuel consumption of BMW model cars by 30%. The composite crankcase, featuring a magnesium alloy housing surrounding an aluminium insert, is the lightest 3.0 litre in-line six-cylinder gasoline engine in the world (161 kilograms) [33]. The resulting magnesium-aluminium alloy engine is 24% lighter than a conventional aluminium engine, simultaneously increasing power performance and fuel efficiency. Design innovation combined with advanced metallurgy enables this environmentally friendly engine the best power-to-weight ratio and lowest specific fuel consumption, requiring fewer parts and less engine assembly work [33]. Mg-Al-Sr magnesium alloy systems and a high pressure die-casting (HPDC) process were created in tandem with the engine's design development to accommodate large volume production.

Mercedes-Benz developed a new 7G-Tronic seven speed automatic transmission without weight increase using magnesium [4]. The engine weight of Audi V8 Quattro model was reduced 5 kg compared to other Audi eight-cylinder by using magnesium components. Steering wheel

Fig. 10 North American automotive magnesium usage [15]

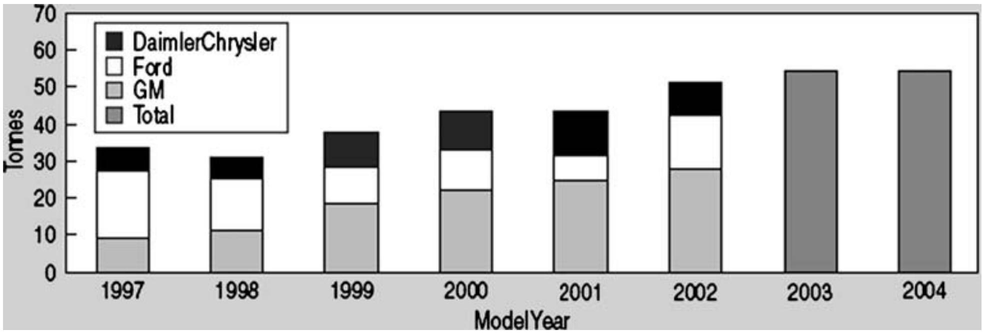


Table 4 Magnesium alloys applications for automotive components [1, 4, 5, 8, 9, 20]

Engine and parts Transmission	Interior parts	Chassis components	Body components
Engine block	Steering wheel cores	Rod wheels	Cast components,
Gear box	Seat components	Suspension arms	Inner bolt lid section
Intake manifold	Instrument panel	Engine cradle	Cast door inner
Crankcase	Steering column components	Rear support	Radiator support
Cylinder head cover	Brake and clutch pedal	Tailgate (AM50)	Sheet compo
Oil pump housing	Air bag retainer		Extruded components
Oil pump	Door inner (AM50)		
Transfer case			
Support (AZ91D)			
cover (AZ91D)			
Cam			
Bedplate			
Engine block (Ford)			
Oil pan (Ford)			
Front cover (Ford)			
Engine cradle (Ford)			

is the component that has received the greatest worldwide acceptance which made of Mg alloy. The Instrument panel (IP) for the GM H-van vehicle is made of magnesium alloy which weights 12 kg as opposed to the 18 kg in steel. The part also offers better crashworthiness and cost saving due to design consolidation [12, 29, 30, 43, 50]. Ford changed the hydro-formed steel, tubular steel, extruded aluminium and molded plastic composites materials with die-cast AM-60 magnesium alloy for front end support assemblies (FESA). AM 50 and AM 20 magnesium alloys have been used in automotive seats structure. Magnesium alloys were chosen over steel, aluminium and plastics. GM has been using magnesium wheels for the Corvette since 1998. Magnesium substitution in the automotive industry has steadily increased over the last decade, in parts such as valve covers, instrument panels, steering wheels, steering wheel armatures, and seat bodies. Mg applications in North American auto industry have risen at a rate nearly 15% per year during the 1990s culminating in a 2002 model average of 4.1 kg per vehicle [12, 15]. Emerging goals for reduced emission and fuel economy in passenger vehicles is exerting a driving force for expanding the use of magnesium [9, 6]. Until the 1970s, the VW Beetle used to be one of the largest consumers of magnesium alloys with a 42.000 tpa consumption [4, 7, 9]. Consumption of magnesium decreased in the early 1970s as the prices of magnesium grow and VW Beetle (Kafer) stopped production in Germany [9]. Development of corrosion resistant AZ91D and AZ91E and high-ductility AM 20 and AM 50 magnesium alloys can be considered as an important achievement of the recent years [4, 31]. These die-casting alloys improve quality of parts and provide an easier process technology. Automotive industry consumes 90% of all magnesium alloys [33]. Standard parts made of

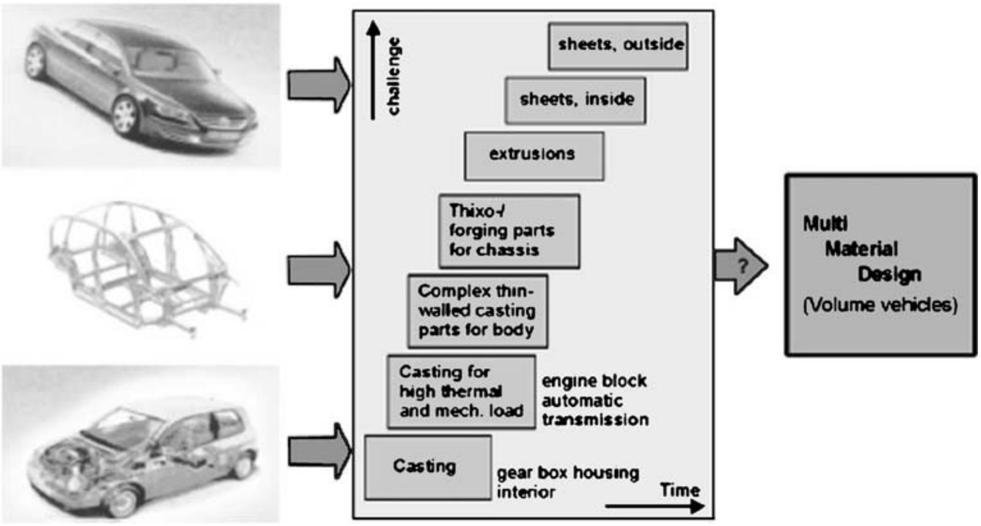


Fig. 11 VW strategy of magnesium technology development [7]

magnesium alloys are: instrument panel, support frame, seat frame, steering wheel core parts, steering wheel frames, cylinder block heads, transmission cases, clutch housings, lower crank cases, intake manifolds, brake and gas pedals. Some magnesium alloy applications in the automotive sector are given on a car model in Fig. 8. From the figure it is seen that 22% to 70% weight reduction is possible for automotive components by using Mg alloys instead of alternative materials [33]. The producer of the Mg alloy component and applications on the car models are given in Table 3. Some of the specific automotive components which are produced from magnesium alloys are given Fig. 9. A single piece of magnesium casting was produced and used by Fiat for the cross beam under the dashboard which replaces an 18 part spot-welded assembly [1]. The pressure die-casting production process necessitated the use of open section member in place of a fabricated box made by spot welding. Figure 10 shows magnesium usage for different car manufacturers in the North American automotive industry [15]. Applications of magnesium alloys in the automobile industry using the die-casting approach have been in components such as instrument panels, steering wheels, steering columns and seat risers. In these applications designers are taking advantage of magnesium's high strength-to-density ratio, excellent ductility combined with attractive energy absorbing characteristics. Current and potential magnesium alloy applications for automotive components are given in Table 4. Volkswagen AG's philosophy regarding using various production processes for manufacturing different automotive components is illustrated in Fig. 11. Taking the standards and other environmental laws into account, automotive producers are going to use 40-100 kg of magnesium alloys per car in the near future [4, 12, 23, 33].

Within the next 8-10 years, the amount of magnesium used in automotive industry is expected to increase by at least 300%. Increasing the amount of Mg alloy per car will contribute to obtaining global goals for reducing greenhouse gases. Recent developments in processing Mg alloys have increased the potential usage of Mg alloys in the automotive industry. The current batch of Mg alloy automotive parts are generally manufactured by casting processes as given above. Additional studies are needed on forming processes of Mg alloys to expand the usage of Mg in the automotive industry in the long run.

6 Conclusion and Summary

Greater demand for reduced emissions and better fuel economy in passenger vehicles are the driving forces behind the expanding the use of magnesium. Environmental conservation is one of the principal reasons for the focus of attention on magnesium to provide vehicle weight reduction, CO_2 emission and fuel economy. Weight reduction through Mg applications in the automotive industry is the effective option for decreasing fuel consumption and CO_2 emissions. Improvements in Mg alloying and processing techniques will make it possible for the automotive industry to manufacture lighter, more environmentally friendly, safer and cheaper cars. The increase in the potential application of magnesium profiles is strongly dependent on the question of whether established forming processes for aluminium and steel can be adopted to magnesium. General applications of magnesium alloys in the automotive industry are casting products. 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. The hexagonal structure of magnesium requires elevated forming temperatures to activate more slip systems and to allow better formability, causing higher energy consumption during processing. The reasonable prices and new alloying and forming techniques, especially sheet and extrusion for Mg alloys, are needed to increase the massive use of Mg and its alloys.

Developed magnesium alloys that withstand higher temperatures will enhance the usage of Mg in manufacturing engine blocks and transmission housings. Recently developed Mg-Al-Sr systems have excellent mechanical properties, good corrosion resistance and excellent castability. Mg alloys with Sr addition has better creep resistance than other alloy systems. The lightest commercial 3.0 litre in-line six-cylinder gasoline engine manufactured in 2007 using Mg-Al-Sr alloy system. A 25% weight reduction and increased power performance and fuel efficiency can be obtained with magnesium alloy engines.

The Teflon resin coating that is obtained with aluminium vapour deposition and finish treatment by Teflon resin will enhance the potential applications of magnesium alloys for automotive industry with its corrosion properties at a lower cost and good lubricating property.

Magnesium alloys can be joined by mechanical assembling and welding. A 22% to 70% weight reduction is possible for automotive components by using Mg alloys instead of alternative materials. The components that are made of Mg alloy have better strength-to-density ratio, ductility and energy absorbing characteristics.

The disadvantages of Mg alloys are high reactivity in the molten state, galvanic corrosion resistance, fire hazard, inferior fatigue and creep. The design of the Mg alloy parts is important for adequate drainage, to prevent the accumulation of corrosive substances, such as water/moisture. Fe, Ni and Cu reduce the corrosion resistance of Mg alloys.

Thus, during the processing of hot/molten Mg alloys, the metal must be shielded by inert gas or flux to overcome fire risk. In machining process of Mg alloys, the fire hazard/risk can be eliminated by avoiding fine cuts, dull tools, and high speeds, using proper tool design to avoid heat build up, avoiding the accumulation of chips and dust on machines and cloths, and using coolants.

Significant research is still needed on magnesium processing, alloy development, joining, surface treatment, corrosion resistance and mechanical properties improvement to achieve future goals to reduce the vehicle mass and the amount of greenhouse gases. Production and application technologies must be cost effective for magnesium alloys to make magnesium alloys an economically viable alternative for the automotive industry.

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