Magnesium and its Alloys for Automotive – A Review

R.Sampathkumar
Lecturer (Senior Grade), Department of Mechanical Engineering, Nachimuthu polytechnic College, Pollachi

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.**

Index Terms- **Magnesium, Mg components, Mg applications. Automotive industry, Transportation, Fuel economy.**

1. INTRODUCTION

Competitive Automobile Market across the world is concentrating on Fuel consumption, strength, reliability, emission and cost. Subsequently latest regulations are very stringent in emissions. Components made with conventional materials are not enough to meet the required standards. Identifying new materials are mandatory to meet the expectation of the customer and competition. New materials are required with good mechanical properties, especially good strength to weight ratio, mechanical and temperature creep, ductility, corrosion resistant and ease in manufacturing. These situations brings lightweight materials and new production processes. Basic requirements for automotive components are shown in fig. 1. New materials like composites of MMC, PMC and conventional light materials with alloying may be considered for the applications. Light alloys decrease the pollution by gas emission. Magnesium is one of the oldest existing material is better suited the above requirements. Magnesium is alloying with other materials make the components required properties.

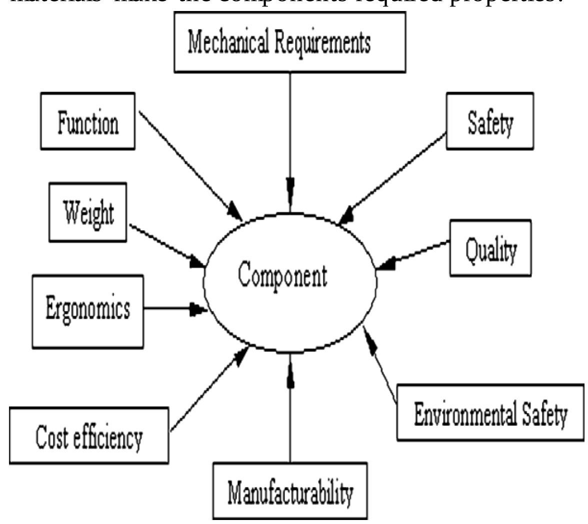

Figure 1: Basic Requirements for Vehicle Components

Weight reduction in automobiles 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 liters per 100 kilometers for a vehicle [12]. High-strength steels, aluminum (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. Significant research is still needed on magnesium processing, alloy development, joining, surface treatment, corrosion resistance and mechanical properties improvement.

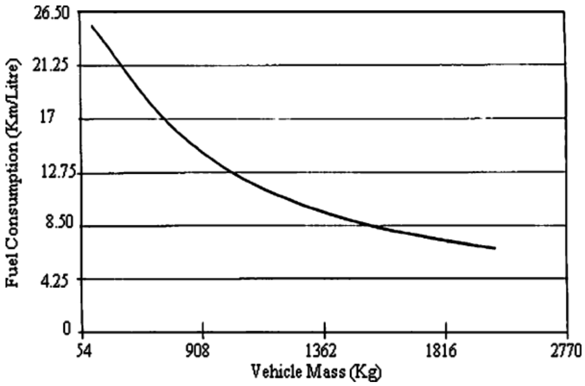

Figure 2: The Relation between Vehicle Mass and Fuel Consumption

MG & ALLOYS

Magnesium (Mg) is the lightest of all structural metals in practical use, with a density of 1.74g/cc. The density of magnesium is approximately two thirds of that of aluminum, one quarter of zinc, and one fifth of steel. The physical properties of Mg, Al and Fe are given in Table 1. There are over 80 different minerals known to have magnesium content of 20% or greater such as dolomite ($MgCO_3.CaCO_3$),magnesite ($MgCO_3$), olivine, carnalite ($KMgCl_3.6H_2O$), etc., making it the eighth most abundant element in the earth's crust. Also magnesium is the second most abundant metal in seawater, after sodium. Hence magnesium can be considered as an inexhaustible resource. However, only dolomite and magnetite form the predominant ingredient for magnesium extraction processes.

However magnesium shows high potential to substitute conventional materials. Magnesium alloys should be used in applications where low mass and high specific properties are required. According to the combination of specific Young's modulus and high specific strength magnesium alloys show similar or even better values than aluminum and many commercial steels (Fig. 1). With the increasing use of magnesium the cost per tone is coming down, which makes it more competitive from the economic point of view too. Magnesium alloys offer a very high specific strength among conventional engineering alloys, light weight, high stiffness, excellent machinability, good dimensional stability and damping capacity. Among the currently used magnesium alloys, the Mg – Al systems (with and without zinc) offer reasonably high strength properties at room temperature and are in wide use. However, compared to other structural metals, magnesium alloys have a relatively low absolute strength, especially at elevated temperatures. (1)

Alloying magnesium with aluminum, 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 aluminum alloys are replaced by magnesium-based alloys. The requirement to reduce the weight of car components as a result of legislation limiting emission has created renewed interest in magnesium.

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. Porsche first worked with a magnesium engine in 1928. 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.

Property	Magnesium	Aluminium	Iron
Crystal structure Density at 20°C (g/cm^3)	hcp 1.74	FCC 2.70	Bcc 7.86
Coefficient of thermal expansion 20–100°C ($\times 10^6$/C)	25.2	23.6	11.7
Elastic modulus [Young's modulus of elasticity] (10^6	44.126	68.947	206.84
Tensile strength (Mpa)	240 (for AZ91D)	320 (for A380)	350
Melting point (°C)	650	660	1.536

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

Alloying of Magnesium

S.No	Material	Density (g/cm3)	Thermal Conductivity (W/mK)	UTS (Mpa)	YTS (Mpa)	Fatigue Strength (Mpa)	Impact (J)	Hardness (BHN)	% Elongation in 50 mm	Specific Heat (J/g-°C)	Coeff. of Thermal Expansion (µm/m-C)
1	AZ91	1.81	72.7	230	150	97	2.7	63	3	0.8	26
2	AM60	1.79	62	241	131	80	2.8	65	13	1	26
3	AM50	1.77	65	228	124	75	2.5	60	15	1.02	26
4	AZ31	1.771	96	260	200	90	4.3	49	15	1	26
5	ZE41	1.84	113	205	140	63	1.4	62	3.5	1	26
6	EZ33	1.8	99.5	200	140	40	0.68	50	3.1	1.04	26.4
7	ZE63	1.87	109	295	190	79	2.3	75	7	0.96	27
8	ZC63	1.87	122	240	125	93	1.25	60	4.5	1	26

Table 2: Magnesium Alloys and Their Properties

Alloying Element	Properties	Effect
Aluminum	Hardness	Increases
	Strength	
	Ductility	Decreases
Beryllium	Oxidation	Decreases
Calcium	Oxidation	Decreases
Cerium	Corrosion resistance	Increases
	Yield strength	Decreases
Copper	Strength	Increases
	Ductility	Decreases
Nickel	Yield and Ultimate Strength	Increases
	Ductility and Corrosion resistance	Decreases
Rare Earth Metals	High temperature creep	Increases
	Corrosion resistance	
	Strength	
Silicon	Corrosion resistance	Increases
Zinc	Corrosion resistance	Increases

Table 3: The Effects of Various Alloying Elements in Magnesium

Research has been conducted on the manufacture of various products by different combination of alloys and its suitability and association of one element over the other. Magnesium contains hexagonal lattice structure which resist the plastic deformation hence majority of Mg alloys are casted. Wrought alloys came into existence in 2003. Casting methods for magnesium are popular and the appropriate amounts of additives improve the strength, cast ability, workability, corrosion resistance and weld ability of these alloys in a well- balanced way (Table 2 lists various alloying elements that can be added to magnesium to improve the properties as per ASTM standards (Avedesian and Baker 1999 and Polmear 1994).

ASTM (American Society for Testing and Materials) names the Magnesium alloys with two letters defining the elements, with numbers denoting the percentage and an additional digit to indicate intermediate properties. For example, AZ 91 Mg alloy contain aluminum (Al) and zinc (Zn) in 9%,1% respectively in total and the rest by pure magnesium. (Avedesian and Baker 1999) 4 Magnesium alloys and their properties (Sameer, Suman 2014).

Table 3 summarizes the effects of alloying elements in magnesium. The combination of alloy elements like Al-Zn , Al-Zn-Mn , Al-Cu, RE-Zr , Zr-Y , Zn-Zr- RE and many more were tried with magnesium and successfully proven to be of advantage (Tarek 2009 and Luo, Pekguleryuz 1994). Statistics were showing that AZ series of alloys are the most commonly used and AZ 91 alloys are popular magnesium alloys with good room temperature strength and ductility . AZ91E shows good corrosion resistance and weldabilty among AZ91 series alloys.

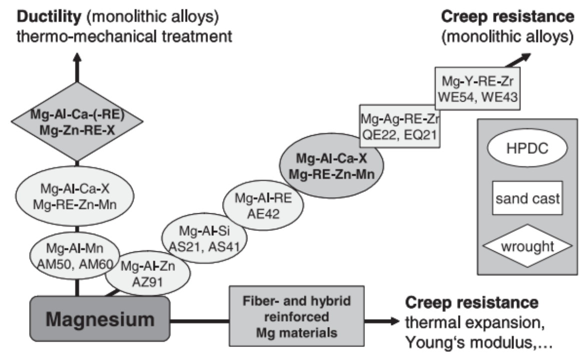

Figure 3: Directions of Alloy Development to Improve the Performance of Magnesium Components

II.PROCESSING METHODS

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

Melting

Molten magnesium does not attack iron in the same way as molten aluminum which has high affinity to iron; thus, magnesium alloys can be melted and held in crucibles fabricated from ferrous materials. It is common practice to melt and process molten magnesium in steel crucibles and deliver it to casting operations in steel tools and devices. Fig. 4 shows the cross-sectional design of a typical fuel-fired stationary crucible furnace, from which metal for small castings can be hand, poured using ladles. This use of metallic crucibles allows the crucible to be supported from the top by means of a flange, leaving a space below the crucible. The furnace chamber has a base that slopes toward a cleanout door. Modern casting operations generally use electrical furnaces with steel covers and melt transfer devices.

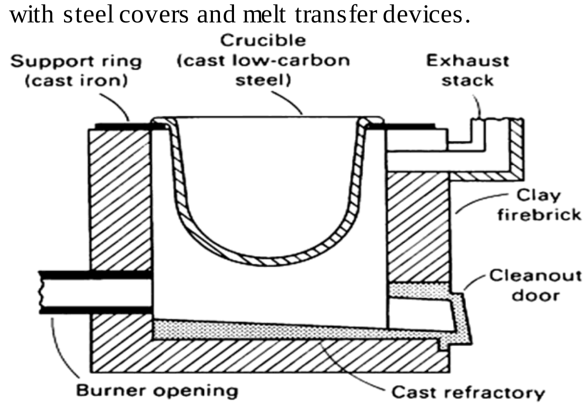

Figure 4: Crucible Furnace

Melt Protection

Molten magnesium tends to oxidize and burn, unless care is taken to protect its surface against oxidation. Unlike aluminum alloys which tend to form a continuous, impervious oxide skin on the molten bath limiting further oxidation, magnesium alloys form a loose, permeable oxide coating on the molten metal surface. This allows oxygen to pass through and support burning below the oxide at the surface. Protection of the molten alloy using either a flux or a protective gas cover to exclude oxygen is therefore necessary. There are basically two main systems, flux and flux less, for the melt protection of magnesium alloys.

Flux Process

Protecting molten magnesium using flux was developed before proper gaseous protection was developed. A typical flux-melting procedure would be for the crucible with a small quantity of flux (about 1% of charge weight) placed in the bottom, to be preheated to dull red heat. Additional flux is lightly sprinkled onto the melt surface during melt holding and casting operations. Since the discovery of sulfur hexafluoride (SF_6) as effective protective gas for magnesium melting and casting, flux melting is limited to casting of special gravity casting alloys with very high melting points.

Flux less Process

Flux less melting using air/SF_6, air/CO_2/SF_6 or CO_2/SF_6 as protective gas mixtures developed in the 1970's was a significant breakthrough in melting, holding, and casting of magnesium alloys. SF_6 has been shown to be an extremely effective oxidation inhibitor for magnesium alloys.

High Pressure Die Casting

High pressure die casting (HPDC) offers attractive flexibility in design and manufacturing of light metals components. The excellent die filling characteristics of magnesium alloys allow large, thin-walled and complex castings to be economically produced by this process, replacing steel structures made of numerous stampings and elements.

Powder Metallurgy

Magnesium and other reinforcement elements are powdered, mixed, pressed and sintered at a temperature under controlled atmosphere. It has potential of high volume fraction of reinforcement but this is a costly process. This technique is not ideal for mass production. A variety of magnesium matrix composites like Al_2O_3/AZ91, SiC/AZ91, TiO_2/AZ91, ZrO_2/AZ91, SiC/QE22, and B_4C/AZ80 have been fabricated through powder metallurgy.

Vapor Processing

CVD (Chemical Vapor Deposition), PVD (Physical Vapor Deposition) vapor processing involves the deposition of thin films by condensation of vaporized desired material on work piece surface. Vapor deposition is a primary process where the matrix is deposited from the vapor phase on to individual reinforcement of ingredients. This process is very slow but there is no mechanical disturbance at the interface region as it is purely a chemical process. This method has been widely adapted to Mg-Al-Zn alloys for surface coatings to improve corrosion resistance.

Squeeze Casting

There are two types of squeeze casting processes: direct and indirect squeeze casting. In both types of the processes, molten metal is introduced to casting cavities with minimum turbulence and solidifies under very high pressure (typically above 100 MPa) within closed dies.

Direct Squeeze Casting

Direct squeeze casting (DSC) is also termed liquid metal forging. As shown in Fig. 11, the direct squeeze casting process consists of metering liquid metal into a preheated, lubricated die and forging the metal while it solidifies. The pressure is applied shortly after the metal begins to freeze and is maintained until the entire casting has solidified. Casting ejection and handling are done in much the same way as in closed die forging.

Indirect Squeeze Casting

While direct squeeze casting is generally performed on a vertical machine (similar to a forging press), indirect squeeze casting (ISC) is more akin to conventional high pressure die casting, using both vertical or horizontal machines. During an indirect squeeze casting such as the "Horizontal Vertical Squeeze Cast" (HVSC) process, molten magnesium is transferred (preferably in an enclosed tube) to the shot sleeve, and then injected into the die cavity through relatively large gates and at relatively low velocity (usually under 0.5 m/s). Melt in the die cavity is then solidified under high pressure “indirectly” applied by the plunger through the large gating system.

III. AUTOMOTIVE APPLICATIONS

Vehicle light weighting is among the available strategies to improve the fuel economy of vehicles of conventional gasoline internal combustion engines or alternative energy powertrains. Magnesium, the lightest structural metal, has emerged as a promising material for light weighting and become a focus of research and development in many countries around the world. Table 6 is a summary of the current major magnesium applications in automotive industry. It shows that magnesium has made significant gains in world-wide interior applications, replacing mostly steel stampings in instrumental panels, steering wheels and steering column components. In the powertrain area, North America is leading the applications of magnesium 4WD (four-wheel-drive) transfer cases in high-volume truck production; while Europe is aggressively expanding the use of magnesium in engine blocks and transmission cases using recently developed creep-resistant magnesium alloys. Only a limited number of body and chassis components are currently made of magnesium, which presents a great opportunity for magnesium to expand its applications in lightweight vehicle construction. This section discusses the current and potential magnesium applications in the vehicle subsystems.

System	Component
Interior	Instrument panel
	Knee bolster retainer
	Seat frame
	Seat riser
	Seat pan
	Console bracket
	Airbag housing
	Center console cover
	Steering wheel
	Keylock housing
	Steering column parts
	Radio housing
	Glove box door
	Window motor housing
Body	Door inner panel
	Liftgate inner panel
	Roof frame
	Sunroof panel
	Mirror bracket
	Fuel filler lid
	Door handle
	Spare tire carrier
Chassis	Wheel (racing)
	ABS mounting bracket
	Brake pedal bracket
	Brake/accelerator bracket
	Brake/clutch bracket
	Brake pedal arm
Powertrain	Engine block
	Valve cover/cam cover
	4WD transfer case
	Transmission case
	Clutch housing & piston
	Intake manifold
	Engine oil pan
	Alternator/AC bracket
	Transmission stator
	Oil filter adapter
	Electric motor housing

Table 6: Global Magnesium Applications in Automobiles

Interior

Since corrosion is of less concern in interior, this area has seen the most magnesium applications, with the biggest growth in the instrument panels (IP) and steering structures. The first magnesium IP beam was die cast by GM in 1961 with a mass saving of 4 kg over the same part cast in zinc. The design and die casting of magnesium IP beams have advanced dramatically in the last decade.

The use of magnesium seat structures began in Germany in 1990’s.

Body

The use of magnesium in automotive body applications is limited but recently expanding. GM has been using a one-piece die cast roof frame since the C-5 Corvette introduction in 1997. Magnesium is also used in the Cadillac XLR roadster’s retractable hard-top convertible roof and the roof top frame. The Ford F-150 trucks and SUVs have coated magnesium castings for their radiator support [34], and Dodge Viper has a one-piece magnesium front-of-dash die casting.

Chassis. Cast or forged magnesium wheels have been used in many high-priced race cars or high-performance roadsters. However, the relatively high cost and potential corrosion problems of magnesium wheels prevent their use in high-volume vehicle production. The first-in-industry one- piece HPDC magnesium cradle for the Chevrolet Corvette Z06 weighs only 10.5 kg, and demonstrates a 35% mass savings over the aluminum cradle it replaced. This cradle uses a new AE44 (Mg-4Al-4RE) alloy which offers high strength and ductility at room- and elevated temperatures.

The production of lightweight and low-cost magnesium chassis components such as wheels, engine cradles and control arms depends on the improvement of magnesium casting processes. Various casting processes have been developed for the production of aluminum wheels and chassis parts. These processes include permanent mold casting, low-pressure casting, squeeze casting and semi-solid metal (SSM) casting. The successful adaptation of these processes to magnesium alloys will make magnesium castings more competitive to aluminum in the chassis area. For example, recent de- velopments in low pressure die casting and squeeze casting will make lightweight cast magnesium wheels, control arms and knuckles more cost-effective in competing with forged aluminum components. The development of low-cost, corrosion-resistant coatings and new magnesium alloys with improved fatigue and impact strength will also accelerate the further penetration of magnesium in chassis applications.

Powertrain

The majority of powertrain castings (such as engine block, cylinder head, transmission case and oil pan) are presently made of aluminum alloys, which represents the most significant opportunity for light weighting with magnesium due to the excellent cast ability of magnesium alloys. The operating temperatures for these applications are below 120°C, and AZ91 is the alloy of choice due to its excellent combination of mechanical properties, corrosion resistance and cast ability.

Higher-temperature applications such as automatic transmissions and engine blocks require creep-resistant magnesium alloys. The Mercedes 7-speed automatic transmission case uses AS31 alloy with marginally better creep resistance than AZ91 alloy. Honda introduced a new alloy referred as ACM522 (Mg-5%Al-2%Ca-2%RE) in the production of Honda Insight (a low-volume hybrid gas/electric car) oil pans, achieved a 35% weight saving over the aluminum design.

IV. CHALLENGES

Future Challenges

While magnesium is the lightest structural metal and the third most commonly used metallic material in automobiles following steel and aluminum, many challenges remain in various aspects of alloy development and manufacturing processes to exploit its high strength-to-mass ratio for widespread lightweight applica- tions in the transportation and other industries.

Material challenges

Compared with the numerous aluminum alloys and steel grades, there are only a limited number of low-cost cast magnesium alloys available for structural applications. The conventional Mg-Al based alloys offer moderate mechanical properties due to limited age-hardening response of this alloy system. Since the development of vacuum die casting and other high-integrity casting processes, magnesium castings can be heat-treated with no blisters. Alloy systems with significant precipitation hardening such as Mg-Sn [57,58] and Mg-RE [59] should be developed with improved mechanical properties. New alloys with improved ductility, fatigue strength, creep resistance and corrosion resistance should also be explored. Computational thermodynamics and kinetics [60] will be used to design and optimize these new alloys. The properties of magnesium alloys can be significantly enhanced if micro- and nano-particles are introduced to form metal matrix composites (MMC). Micro- and nano-sized particles offer strengthening mechanisms in different length scales and provide a tremendous opportunity for a new class of engineering materials with tailored properties and functionalities for automotive applications.

Process challenges

Although the success of magnesium is primarily attributed to its superior die-castability compared with aluminum alloys, these castings cannot generally be heat-treated due to the porosity intrinsic to die casting that is present. Several recent developments show promise including super vacuum die casting and squeeze casting that drive porosity to minimal levels to enable their heat treatment without blistering. Com- bined with advanced low-cost alloys, these processes could provide competitive advantages for increased use of magne- sium die castings. Other casting processes such as gravity, permanent mold, low pressure and ablation casting, have also been adapted for magnesium although casting rules developed for aluminum need to be modified to compensate for the larger shrinkage with magnesium. These processes are still, never- theless, important for magnesium due to the need for large hollow castings for structural subsystems like engine cradles that provide the highest mass efficiency. Melt handling, molten metal transfer with minimal turbulence, grain-refinement, die coating as well as casting parameters need to be developed specifically for magnesium alloys to fully utilize their intrinsic properties in these casting processes.

Performance challenges

There are several performance-related challenges that need significant research efforts.

Crashworthiness

Magnesium castings have been used in many automotive components such as the instrument panel beams and radiator support structures. High-ductility AM50 or AM60 alloys are used in these applications and performed well in crash simulation and tests; and many vehicles, with these magnesium components, achieved five-star crash rating. A recent study shows that magnesium alloys can absorb significantly more energy than either aluminum or steel on an equivalent mass basis.

Noise, Vibration and Harshness (NVH)

It is well known that magnesium has high damping capability, but this can be translated into better NHV performance only for mid-range sound frequency; 100-1000 Hz. The low- frequency (<100 Hz) structure-borne noise can be controlled by the component stiffness between the source and receiver of the sound.

Fatigue and Durability

Fatigue and durability are critical in magnesium structural applications and there is limited data in the literature. Multi-scale simulation tools can be used to predict the fatigue life of magnesium components and sub- systems, which can be validated for automotive applications.

Corrosion and Surface Finishing

Pure magnesium has the highest standard reduction potential of the structural automotive metals. As noted earlier, while pure magnesium (at least with very low levels of iron, nickel, and copper) has atmospheric corrosion rates that are similar to that of aluminum, magnesium's high reduction potential makes it very susceptible to galvanic corrosion when it is in electrical contact with other metals below it in the reduction potential table. The impact of this susceptibility to galvanic corrosion on the application of magnesium in exposed environments is severe in both the macro- environment and the micro-environment. A major challenge in magnesium automotive applications is to establish the surface finishing and corrosion protection processes. The challenge is two-fold since surface treatments for magnesium play roles in both manufacturing processes (e.g., adhesive bonding) as well as the product life cycle that demands corrosion resistance. Future research will explore novel coating and surface treatment technologies including pretreatments such as micro-arc oxidation, non-chromated conversion coatings, and "cold" metal spraying of aluminum onto magnesium surfaces.

V. CONCLUSION

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, CO2 emission and fuel economy. 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 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.

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. It is expected that future developments exploiting the new computational and characterization tools available will provide the much needed breakthroughs to design new magnesium alloys and engineering products to increase the use of magnesium, the lightest structural metal.

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