

Corrosion behavior of magnesium and magnesium alloys^①

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Abstract: The automotive industry has crossed the threshold from using magnesium alloys in interior applications such as instrument panels and steering wheels to unprotected environment such as oil pan, cylinder head and wheels. The expanding territory of magnesium leads to new challenges: mainly environmental degradation of the alloys used and how they can be protected. The present critical review is aimed at understanding the corrosion behavior of magnesium and magnesium alloys in industrial and marine environments, and the effect of microstructure, additive elements and inhibitors on the corrosion mechanism.

Key words: magnesium alloys; corrosion; protection; automotive industry

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1 INTRODUCTION

Magnesium alloys were used extensively between 1910 and 1945. The first magnesium piston was invented in 1921 by Tommy Milton and used for 804 km in Indianapolis USA, and Electrometal company produced nearly four million magnesium pistons between 1926 and 1937. However, stringent mass constraints in automobile industry, because new legislations concerning global emission control have led to the use of ultra light materials such as magnesium alloys. It is the most cost-effective option for significant decreasing of fuel consumption, CO_x and NO_x missions^[1, 2].

In recent years, corrosion of magnesium alloys have limited their applications. The susceptibility of

magnesium alloys to corrosion in aqueous environments has a serious concern. Studies on magnesium and its alloys have been carried out to understand the corrosion behavior in various aqueous electrolytes^[3-5].

In this study, the corrosion behavior of magnesium alloys intended for use in automobile industry and electronic applications is reviewed emphasizing on the effect of microstructure on the corrosion of new alloys.

2 STRUCTURAL MAGNESIUM ALLOYS

Magnesium alloys have been developed during the years from addition of zirconium, thorium, lithium, silver and rare metals to less expensive elements such as aluminum, zinc, manganese, silicon and ca-

Table 1 Compositions and properties of magnesium alloys

Alloy	Mass fraction/ %	σ_b / MPa	σ_s / MPa	δ / %	ρ / (g \cdot cm $^{-3}$)	Corrosion
AZ91D	9Al, 0.7Zn, 0.17-0.4Mn	230	160	3	1.81	2
AM60B	6Al, 0.2Zn, 0.15-0.5Mn	220	130	6-8	1.78	2
AM50A	5Al, 0.2Zn, 0.28-0.5Mn	220	110	6-10	1.78	2
AM20	2Al, 0.23Mn	210	90	12	1.78	2
RZ5	4.2Al, 1.2Re, 0.7Zr	218	148	4	1.78	2
MEZ	2.5Al, 1.2Re, 0.35Zn	172	145	5	1.78	2
ZAC8506	8Zn, 5Al, 0.6Ca	219	146	5	1.8	2
AMC5006	5Al, 0.6Ca, 0.32Mn	156	95	8.5	1.78	3
MRI 151		277	17.5	7.5		3
MRI 177	Under patient process	275	177	6.7		3
Noranda A1		202	145			3

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cium, as shown in Table 1. The search for low mass, high strength and creep resistance has led to addition of many other metals such as strontium, scandium and tin. Unfortunately most of these additions have limited effect on corrosion resistance.

3 MAGNESIUM CORROSION THERMODYNAMICS

The anodic reactions of magnesium in an aqueous solution in the absence of a complex-forming or precipitating anions other than hydroxyls, follows the general oxidation reactions proposed by Hoar^[6]. The E —pH diagram^[7] for magnesium metal in Fig. 1 shows that magnesium hydroxide is stable only above pH 10.0, and the standard reduction potential of magnesium is 2.4 V with respect to the standard hydrogen electrode, which indicates that magnesium is an active metal.

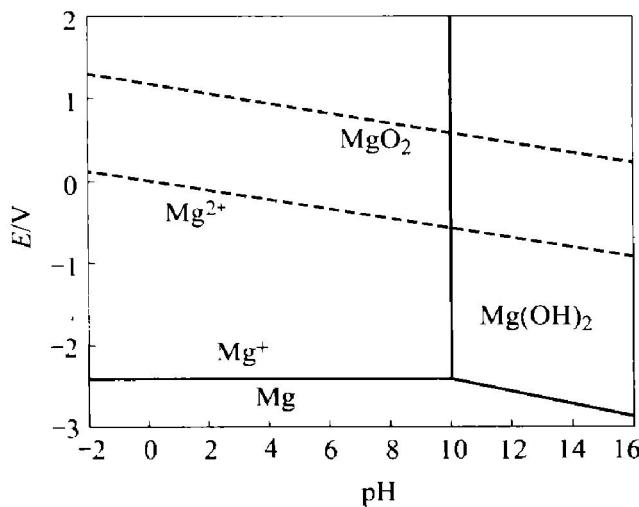


Fig. 1 E —pH diagram of magnesium metal

The typical anodic dissolution of magnesium is metal oxidation:



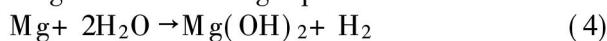
The cathodic reaction is generally believed to be hydrogen evolution:



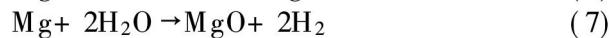
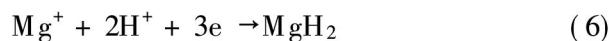
With the increase of pH the magnesium hydroxide deposits on the metal surface:



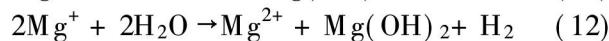
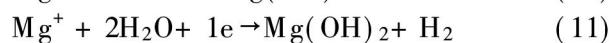
Greenblatt et al^[8, 9] believe that the mechanism of magnesium reactions in aqueous solutions takes place in many steps. Magnesium reacts with water as a self corrosion reaction (with no external current) according to the following equation:



The fourth reaction has many intermediates such as Mg^+ , MgH_2 and MgO which depends on the metal potential. These intermediate compounds were reported by many researchers^[10, 11]:



Further reactions of intermediate compounds (Mg^+ , MgOH , and MgH_2) with hydroxide or water lead to the formation of more stable magnesium hydroxide film on the metal surface:



The formation of hydroxide/oxide films over the surface is responsible for masking and reducing the effective anodic area as well as the anodic dissolution^[12]

According to Petty et al^[13], the formation of monovalent Mg^+ spaces (reaction (5)) and its reaction with water to generate more hydrogen (reaction (12)) explains the negative difference effect (NDA) phenomenon^[14, 15]. It is found experimentally that when the anodic over voltage is increased, the cathodic hydrogen evolution reaction increases rather than decreases.

Recently^[16], two steps dissolution processes of magnesium were proved experimentally. At the low potential of -2.78 V (vs SCE), the monovalent process takes place, while at high potential of -1.56 V (vs SCE) the divalent process takes place.

The electrochemical behavior of magnesium in acid and in neutral solution is an active metal dissolution with no deposition of magnesium hydroxide on the metal surface, respectively. This leads to a substantial increase in pH^[17]. However, as soon as the pH of the surface film reaches a value of 11 for $[\text{Mg}^{2+}] = 10^{-5}\text{ mol} \cdot \text{L}^{-1}$ ^[17], a sparingly soluble magnesium hydroxide is formed on the metal surface and protects the metal from further dissolution.

4 ATMOSPHERIC CORROSION

Magnesium alloys are less resistant to atmospheric corrosion than aluminum alloys, but considerably more resistant than low-carbon steels.

4.1 Effect of humidity

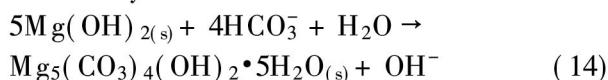
Corrosion of magnesium increases with relative humidity increasing, at low humidity of 10% neither pure magnesium nor many of its low purity types show evidence of surface corrosion after 18 months of exposure. However, as the humidity increases beyond 30%, slight visible corrosion becomes evident, and as the humidity increases to 80%, the metal surface shows a considerable corrosion^[18] and the surface film is composed mainly of magnesium hydroxide^[19].

4.2 Effect of carbon dioxide

Carbon dioxide gas dissolves in water or humidity droplets to form carbonic acid which reduces the pH of the solution according to the following reaction:



In 1933, Whitby^[20] suggested that the reaction of carbon dioxide with magnesium would result in magnesium carbonate, which is a sparingly soluble compound and provides some protection to the metal. Carbonates may also form as follows^[21]

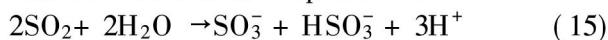


X-ray diffraction analyses of corrosion products scraped from magnesium ingots after 18 months of exposure in a rural atmosphere^[22] have shown the presence of $\text{MgCO}_3\text{H}_2\text{O}$, $\text{MgCO}_3 \cdot 5\text{H}_2\text{O}$ and $3\text{MgCO}_3 \cdot \text{Mg(OH)}_2 \cdot 3\text{H}_2\text{O}$. The magnesium hydroxyl carbonate is a non-conducting compound and it can not serve as a substrate for the cathodic reaction, this compound also can slow the corrosion of magnesium by blocking the anodic sites when it is deposited on the metal surface.

4.3 Effect of sulfur dioxide

Sulfur dioxide, if dissolved in an adsorbed film of water (condensate, cloud or rain), is generally oxidized to sulfuric acid (as in the case of carbon dioxide) and the acid will attack the exposed metal to give sulfate compounds. In general, the corrosion rate of steel, zinc and magnesium in industrial sites is two to five times higher than that in rural sites^[23].

During the wetness period, the pH of the thin layer of condensate that is formed on the magnesium or magnesium alloy surface becomes acidic due to the formation of sulfuric acid by oxidation of sulfur dioxide. This leads to the dissolution of the slightly soluble Mg(OH)_2 or the less soluble magnesium hydroxyl carbonate, and the formation of more soluble $\text{MgSO}_3 \cdot 6\text{H}_2\text{O}$ or kieserite $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$. These compounds are detected by X-ray diffraction analysis of magnesium corrosion products formed after long exposure of the metal to industrial atmosphere^[22].



It is evident that the decreasing pH on the metal surface by sulfur dioxide prevents the formation of low solubility compounds and leads to continuous corrosion of the magnesium or magnesium alloy exposed to such environment.

4.4 Effect of chlorides

Hydrogen chloride (HCl) is a highly soluble and reactive gas and one of the acidifying pollutants in atmosphere. In many countries coal combustion (which contains 0.1% - 0.4% chloride) is the major source of with incineration of polymers, being the next largest contributor. Chlorides exist as a part of ma-

rine atmosphere in costal areas.

The main role of hydrogen chlorides is to reduce the pH of the water layer on magnesium or magnesium alloys surface below which the dissolution of magnesium hydroxide or magnesium hydroxyl carbonate takes place.

Pitting initiation of magnesium may take a similar way observed on aluminum and its alloys. Sumuels et al^[24] considered a four steps pitting initiation mechanism, which include adsorption of halides, complexing with metal, diffusion of soluble compounds (MgCl_2) and finally thinning and cracking of the surface film.

Corrosion of magnesium in sodium chlorides solution is reported to form a dark adhered film. XRD analysis reveals that it contains magnesium hydroxide and magnesium oxy-chlorides ($\text{MgO} \cdot \text{MgCl}_2$) which remain at the end of the test^[16]. Pitting is not the most apparent form of attack for magnesium in chloride solutions, and other forms of corrosion exist, such as exfoliation crevice and stress corrosion cracking. The critical concentration of chlorides, which causes pit initiation on a number of magnesium alloys, falls in the range of $0.002 \text{ mol} \cdot \text{L}^{-1}$ to $0.2 \text{ mol} \cdot \text{L}^{-1}$ NaCl ^[25].

4.5 Effect of impurities and alloying elements on corrosion of magnesium metal

The effect of heterogeneity on magnesium and magnesium alloys corrosion is well documented. Hanawalt et al^[26] described specific effects of alloying elements and impurity phases on corrosion rate sixty years ago. These impurities often lead to severe local attack (pitting), and invalidate electrochemical corrosion rate measurements, as shown in Fig. 2.

It is evident that zinc, cadmium, calcium and silver, have a low moderate accelerating effect on corrosion rates. Whereas, the impurity of heavy metals such as copper, nickel, cobalt and iron, has extremely degrading effect because of their ability to serve as an active cathodic sites for the reduction of water or hydrogen evolution^[27].

On the other hand, manganese, sodium, silicon and tin, have no effect on corrosion of magnesium in salt solutions. Further work^[28] shows that many other elements such as thorium, zirconium, beryllium, cerium, praseodymium and yttrium have little if no any damaging effect on pure magnesium corrosion exposed to 3% salt solution.

4.5.1 Effect of aluminum on corrosion of magnesium aluminum alloys

Aluminum is one of the most important elements added to magnesium to improve castability, mechanical properties and corrosion resistance. It has been

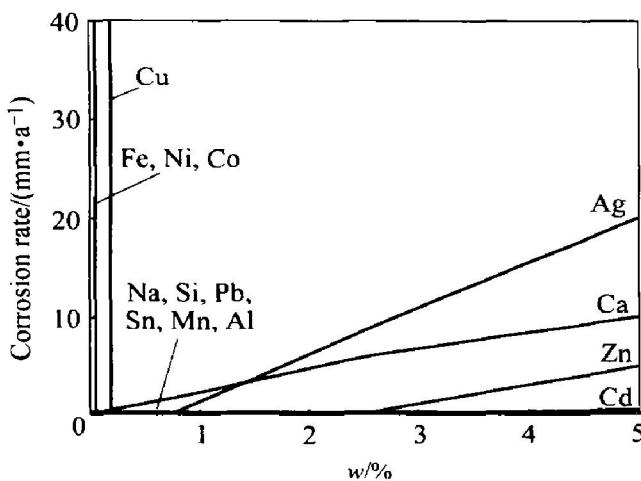


Fig. 2 Effect of impurities and alloying elements on corrosion of magnesium metal in 3% NaCl solution^[26]

observed that, in alloys containing more than 8% Al the corrosion resistance of cast Mg-Al alloys is improved whereas the trend is reversed at lower concentrations^[29].

Aluminum manganese and aluminum zinc magnesium alloys are dual phase alloys of α -Mg matrix (Mg-Al-Zn solid solution with cph crystal structure as pure magnesium) and β precipitate represented with the chemical formula $Mg_{17}Al_{12}$. The corrosion of magnesium aluminum alloys depends on the effect of environment on α and β phases.

Lunder et al^[30] believed that β phase in AZ91 acts as an inert corrosion barrier, and since it is stable in a wide range of pH (4 - 14), the corrosion potential of this phase is close to pure aluminum in neutral and mildly acidic solutions, and that leads to the reduction of corrosion rate of magnesium aluminum alloys.

Further work^[21, 31, 32] has revealed that β phase has two effects on corrosion: as a barrier and as a galvanic cathode. At low aluminum volume fraction, β is a cathode which causes more corrosion of the α phase and at high concentrations it represents an anodic barrier to inhibit the overall corrosion of the alloy.

4.5.2 Effect of zinc in corrosion of magnesium alloys

One of the aims of alloying magnesium with zinc, manganese or aluminum is to form intermetallic compounds with iron, which is also true for magnesium alloys. This addition leads to reducing the intermetallic corrosion as a local action cells^[33].

The binary addition of zinc at levels above 4%

markedly increases the dissolution rate of magnesium alloy, whereas the dissolution of magnesium-4% and 8% zinc is significantly reduced by the addition of manganese^[34]. Previous work^[35] for laser rapid solidifying has shown that the zinc concentration above the equilibrium solid solubility in magnesium (8.4%) gives rise to galvanically active β -Mg₇Zn₃ in α magnesium matrix, the increase in distribution of β -phase, the substantial increase in the corrosion rate in 3% NaCl solutions.

4.5.3 Effect of manganese

Manganese is thought to be partly effective in settling iron from the melt and promoting the formation of intermetallic phases that combine with iron to reduce their effect on the corrosion of magnesium alloys^[8, 36].

The state of the problem is as follows: the solid solubility of manganese in magnesium alloys at room temperature is very low (< 0.1%). Therefore, excessive manganese in magnesium alloy which is not combined with iron or copper impurities (to form intermetallic precipitates) can serve as a cathodic reaction site. It was recommended to keep a low Fe/Mn concentration ratio in order to assure a sufficient availability of manganese^[37]. Fe/Mn ratios lower than 0.021 and 0.032, respectively, were suggested for AM60B and AZ91D alloys produced by die casting methods. A more general concentration of 0.5% to 1.3% Mn was suggested to be added to magnesium aluminum alloys. It was thought that this concentration will enhance the formation of ternary phases^[16].

4.5.4 Effect of calcium

The addition of calcium to magnesium aluminum or magnesium zinc alloys improves substantially the creep resistance, refines the precipitates, decreases the β -phase concentration and forms the high melting precipitates (Al₂Ca). According to Haferkamp et al^[38], the addition of 0.1% calcium to magnesium-12% lithium shows a sufficient corrosion resistance in synthetic sea water^[52].

Further work^[39] on the addition of calcium to AM50 magnesium alloy shows that calcium suppresses formation of β -Mg₁₇Al₁₂ and the formation of more stable Al₂Ca. The decrease or elimination of β -phase may decrease the corrosion rate due to that β -phase often represents the cathodic area in corrosion of magnesium alloys.

Calcium addition to magnesium also improves the high temperature resistance. It was reported^[40] that the addition of as low as 1.5% calcium to pure mag-

nesium leads to the formation of a dense, thin and compact oxide layer on magnesium-calcium alloy exposed at 500 °C for 1 h. The protective oxide layer was composed of magnesium oxide (MgO) and calcium oxide (CaO).

4.5.5 Effect of miscellanies alloying elements

Silicon addition to magnesium aluminum alloys such as AS21 enhances the formation of many intermetallic precipitates within the grains such as Mg₂Si and Mg₁₇Al₁₂ as well as Mn₅Si₃ and β -Mn(Al, Si) phases unsettled during the melting. The Mg₂Si particles are well known to act as pit initiation sites of local action corrosion cells^[41, 42] and the β -Mg₁₇Al₁₂ and β -Mn(Al, Si) represent the cathodic area in the corrosion of magnesium silicon alloys (see effect of Al and Mn on the corrosion of magnesium alloys). This leads to a substantial increase of the corrosion rates of magnesium silicon and Mg-Al silicon alloys which prevent them from further applications, despite of their high mechanical performance^[43, 34]. Table 2 shows the corresponding precipitates of each metal used as an alloying element for magnesium alloys.

Table 2 Intermetallic precipitates of different elements added to magnesium alloys

Group	Metal	Precipitates
1	Al	Mg ₁₇ Al ₁₂
	Mn	Mn ₅ Al ₂ Fe, Mn ₅ Al ₂ Cu (in presence of Al and Fe or Cu)
	Zn	MgZn ₂ , MgZn ₃ , β -Mg ₇ Zn ₃
	Si	Mg ₂ Si
2	Ce	Mg ₁₂ Ce, Mg ₁₂ (La _{0.43} Ce _{0.5})
	Sb	Mg ₃ Sb ₂
	Ca	Al ₃ Ca (in presence of Al)
	Sc	MgSc, Mg ₂ Sc (in presence of Mn \rightarrow Mn ₂ Sc)
	Nd	Mg ₃ Nd, Mg ₁₂ Nd
	Gd	MgGd
	Th	Mg ₃ Th, Mg ₂ Th, Mg ₂₃ Th ₆

The effect of alloying elements and hence the precipitated intermetallics formed on mechanical properties, and the corrosion resistance of magnesium alloys for group one in Table 1 (especially Al and Mn) have been researched extensively in many papers, whereas the published work for group two is scarce and mainly concerned with mechanical properties such as tensile strength and creep resistance.

5 COMPATIBILITY AND GALVANIC CORROSION

Although an outstanding improvement in intermetallic corrosion of magnesium alloys has been achieved by using high purity magnesium alloys. The galvanic corrosion of dissimilar metals remains a concern for design and production engineers in developing magnesium components.

The degree of galvanic corrosion is strongly influenced by the compatibility of the second metal in contact with magnesium parts. Since all structural metals and alloys are cathodic to magnesium and magnesium alloys, as well known from electromotive series of metals and alloys, the degree to which the corrosion of magnesium alloy is accelerated depends partly on the relative positions of the second metal in the series, and the ease of formation and liberation of hydrogen gas (which is the main cathodic reaction product) at the other metal representing the cathode. Therefore, metals such as iron, nickel and copper cause severe corrosion. Metals that combine active potentials with higher hydrogen over-voltage, such as aluminum, zinc and tin are more compatible with magnesium alloys.

One of the few published papers shows that the galvanic corrosion of AZ91hp with Gk-AlSi₆Cu₄ or GD-AlSi₉Cu₃ is much more than the galvanic corrosion of AZ91 when coupled to AlMgSi 0.5 (6060) in 3% NaCl solution^[44].

6 STRESS CORROSION CRACKING OF MAGNESIUM ALLOYS

Stress corrosion cracking generally occurs in systems where a metal or alloy is dissolving at an extremely low rate and experiences localized attack which may become a crack initiation site due to applied stress^[45]. This is usually the case, but not necessarily, involving the break-down of the surface film.

Most of previous investigations of stress corrosion cracking in magnesium based alloys were conducted in aqueous chromate/ chloride solutions because of their relevance to service conditions. Additional environments causing stress corrosion cracking include distilled water^[46] and an aqueous sodium sulfate^[47]. Most of these studies concluded that the cracking was usually transgranular, although certain heat treatments (such as annealing from 345 °C) could activate the intergranular mode owing to grain size effects (fine grains) and grain boundary precipitation^[48].

Transgranular cracking involves quasi cleavage on micro-structural features, possibly twin boundary interfaces^[46]. Similar fractures were reported for AZ91 ruptured by tensile and impact tests in air^[49] and this study showed that the crack propagation primarily occurred near the β -phase particles and grain boundaries, especially in the Mg/Mg₁₇Al₁₂ interface.

The low potentials involved in the cracking of

Mg-Al alloys in chloride-chromate solutions and the obvious discharge of hydrogen gas bubbles during stress corrosion tests, suggest that the mechanism of crack growth is likely to involve hydrogen ingress into the metal which is known as hydrogen embrittlement^[47]. The role of pitting appears to disrupt the surface film which prevents the ingress of hydrogen.

Ebtehaj et al^[50] thoroughly investigated the role of the chloride/ chromate solution concentrations on the cracking of a Mg-9Al alloy, suggested that the susceptibility to cracking was always at a chloride/ chromate ratio near to unity for plain and notched specimens. They also observed that raising the potential above the open circuit value increased cracking susceptibility and lowering the potential decreased susceptibility with respect to the cracking observed under open circuit conditions.

This apparent contradiction (with comparison to stress corrosion cracking of other metals such as aluminum and steel alloys) can be attributed to negative difference effect observed with magnesium alloys, that anodic polarization stimulates hydrogen discharge to a great extent than cathodic polarization does.

In general magnesium alloys containing more than 1.5% aluminum are susceptible to stress corrosion cracking and the tendency increases with aluminum concentration^[51].

7 CORROSION FATIGUE

Substantial reductions in fatigue strength of magnesium alloys have been shown in laboratory using NaCl spray or drops tests. Such tests are useful for comparing alloys, heat treatments and protective coatings.

Fatigue initiation seems to occur at surface or beneath the surface defects such as porosity or contraction cavities. It is well known that most of the casting processes used now producing magnesium alloys with some casting defects. Recent work on fatigue cracking in air of AZ91 has shown that the crack propagation occurs mainly by the coalescence of smaller cracks along the incoherent β -phase. That means the places of contact between the magnesium α phase as (cph) and the β -phase (bcc) is a weak line that cannot withstand high stresses.

8 CORROSION INHIBITION

The use of corrosion inhibitors to slow down corrosion reaction has been, and remains, a widely used technique.

Corrosion inhibitors can be utilized to reduce the corrosion of magnesium alloys used in automobiles in many ways such as the addition of chemicals to cooling water, engine and gearbox oils. They are also used in coatings, primers and paints to prevent corro-

sion of structures such as wheels, oil pan, cylinder head cover alternator and housings, as well as in internal structures such as panels and door frames.

8.1 Coatings of magnesium alloys

Coatings are considered as the most important and complicated system in automotive industry. It provides corrosion and wear resistance as well as an attractive appearance. They can protect the substrate by providing a barrier between the metal and its environment and through the effect of inhibitors used. In order for a coating to provide adequate corrosion protection, the coating must be uniform, well adhered, pore free and self-healing for applications where mechanical damage may occur.

8.1.1 Inorganic surface treatment

Since the year of magnesium alloys using in aerospace applications, a wide range of technologies were developed for cleaning, surface pretreatment and coating. These methods can be described briefly as follows:

1) Electroplating

Nickel gold or gold plating of magnesium alloys have been used in a variety of space applications to improve electrical conductivity and protect the alloy against corrosion^[52]. Electroless nickel plating has been proven useful in the computer and electronics industries for corrosion and wear resistance^[53]. However, any plating method has not been developed that can produce coatings to withstand marine conditions, thereby limiting the use of magnesium alloys in the interior automotive industry, compared with nickel and chrome electroplating.

The electroplating and many inorganic coating processes are all faced with two main challenges. The first is that magnesium is more reactive to form the hydroxide film on the surface, and that needs be removed before coating or pretreatment with chemicals, many of which environmentally are unacceptable (such as chromates and VOC compounds). The second is that the presence of intermetallics or impurities leads to inhomogeneous plating with the formation of pinholes and the intermetallics represent another cathodic site on the metal surface. This situation enhances the formation of local action cells and internal galvanic corrosion.

2) Conversion coatings

Conversion coatings are produced by chemical or electrochemical treatment of a metal surface to produce a superficial layer of substrate metal oxides, and chromates phosphates or other compounds that are chemically bonded to the surface are used. There are a number of conversion coatings used mainly for alu-

minum alloys and can be used for magnesium alloys such as phosphate/ permanganate and fluorozirconate treatments. The mechanism of the formation of chromate conversion coatings is believed to be due to the formation of metal oxide and chromium oxide/ hydroxide on the metal surface^[54-56].

Unfortunately, chromate compounds have been shown to be highly toxic carcinogens. Phosphate- permanganate treatments are being explored as an alternative to chromate conversion coatings. These treatments are more environmental friendly and have been shown to have corrosion protection comparable with chromate treatment. Reviewing the literatures, many alloys have been treated with this method such as AZ91 and WE43A^[57], AM 60B^[58] and AZ91D^[59].

A process for creating stannate^[60] or stannate and zincate^[61] based conversion coatings on magnesium (ZC71+ 12% SiC) and AZ91B+ 0.5% Si has been developed. It is found that a crystalline coating film of $MgSnO_3$ is formed in 30 min of 3 - 5 μm in thickness. The corrosion protection of Ce (NO₃), Ca (NO₃) or Pr (NO₃) solutions has been also investigated and unadherent film is formed on the metal surface.

The primary function of the conversion coatings and pretreatments are to provide a suitable surface to promote the adhesion of subsequent organic coatings. Conversion coatings are not regarded as protective coatings, unless they are to be exposed only to non-corrosive environments.

8.1.2 Organic coatings

Organic coatings are used in the final stage as a top coat. These coatings can be applied to enhance corrosion resistance, abrasion and wear properties as well as decorative purposes. Organic coating systems include a variety of different processes such as painting, electrostatic powder spraying, and cathodic epoxy electro coating (E-coating).

The primary function of organic coatings is to act as a barrier between the metal substrate and its environment. It is important that these coatings provide resistance to transport of ions, water and oxygen. In applications where physical damage is likely to occur (such as in automobiles), it is also important that the coating has a self-healing characteristics. This can be accomplished by the presence of corrosion inhibiting primers or inhibitors added to the coating^[62]. Many compounds have been used as corrosion inhibitors in primers or in coatings for magnesium alloys, some of

them as zinc chromate^[63] and strontium chromate^[64], zinc molybdate, zinc phosphate and organo-zinc salt pigments are also present as corrosion inhibitors for magnesium alloys and they are also effective in inhibition of ferrous alloys.

Adhesion and subsequent corrosion protection to cleaned and pretreated magnesium alloys are enhanced by the use of alkali resistant organic coatings. Polyvinyl butyral, acrylic, polyurethane, vinylepoxy and baked phenolic are generally suitable polymers for coating of magnesium alloys^[65].

8.2 Automotive coatings

Coating used for structural applications in automotive industry is a very complicated process, and more than four layers are often used to offer corrosion, wear, scratches and chipping resistance as well as an attractive appearance. The accumulated experience in coating of automobiles is mainly for carbon steel and aluminum alloys which have been used for many years. However, few papers have been published for the coating of magnesium alloys.

The most important experience is that the production of Mg-Al (3L-Lupo) Volkswagen hatchback^[66]. The inner components of the hatchback are fabricated from die cast magnesium alloy AM50 and covered with aluminum panels from the outside. The magnesium parts underwent cleaning, acid picking, chromating, E-coating and finally powder coating prior to bonding and folding to the pickled aluminum parts. The whole component was then cleaned, phosphated and E-coated to provide maximum protection.

Another attempt^[67] to use a multicomponent coating process for finishing magnesium alloys with first class, a surface quality has also been developed. It refers to the glossy, smooth appearance that is required for readily visible, outer surface of automobile. The process involves applying a conversion coating to the surface followed by the application of a filler which is silicon modified polyester containing corrosion inhibitor, and finally painting with a base coat and clear coat.

8.3 Uses of magnesium alloys

The largest end use for magnesium is as an addition to aluminum based alloys. In 2001 the total shipments of magnesium to aluminum industry was 142 810 t, accounting for 45%. And the second largest user is in gravity and die-casting which represent

33% of the total world wide production. The use of cast alloys is limited to automobile industry but also in many electronic devices as shown in Tables 3 and 4.

Table 3 Applications of magnesium alloys in automotive industry

Company	Parts	Model	Alloy used
Ford	Steering column	Ranger	AZ91HP
	Oil pan, clutch housing		AZ91B
	Manual transmission case	Bronco	AZ91D
GM	4 WD transfer case	Aerostar	AZ91D
	Valve cover, air cleaner, clutch housing	Corvette	AZ91HP
Chrysler	Cylinder head	GMH	AZ91HP
	Instruments panel beam		
Honda	Oil pan, drive brackets	Jeep, Viper	
	Cylinder head cover	City Turbo	AZ91D
	Wheels	Prelude	AM60B
Volks wagen	Gearbox housings. B80, MQ350, MQ200	AZ91	
	Steering wheel, other interior parts.		

Table 4 Applications of magnesium alloys in electronic devices

Company	Products	Parts
Sony	Digital cameras, digital video recorder DSR200	Frame
	Portable MD player MJ-E50.	Frame
	Camera recorder AJ-D700	Frame
National	Portable MD player MJ-SJ7, SJ5	
	TV TH-21 MA9	
SEIKO-Epson	Projector ELP5500/5600	Frame
NEC	Mobile phones	Frame

9 CONCLUSIONS

According to the data obtained, more research work is needed in the following fields in order to enhance utilization of magnesium alloys in automotive and electronic applications:

- 1) Finding of environmentally acceptable pretreatments and coating compounds.
- 2) Investigating the role of precipitates on the corrosion of magnesium alloys.
- 3) Exploring the compatibility of magnesium with other alloys.

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