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REVIEW ARTICLE

The Potential of Magnesium-Based Materials for Engineering and Biomedical Applications

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Abstract | Magnesium (Mg) is the lightest structural metal available in abundance on earth crust. It is an excellent candidate for weight critical applications. For example, the replacement of currently used aluminium alloys in transportation sector by magnesium materials would promote fuel energy savings and emission control. In recent years, there is a growing interest on the utilization of Mg materials for biomedical applications. This is primarily due to the bioresorbable and nontoxic nature of Mg which makes it an ideal choice for body implants. This paper therefore deliberates on the properties of Mg-based materials for potential use in various engineering and biomedical applications. The development of Mg-alloys and composites are discussed in detail, highlighting the influence of various alloying elements and reinforcements. The processing methods applicable for Mg materials are briefly introduced, followed by a summary on the current trends and the actual use of Mg-based materials in automobile, aerospace, consumer electronics, and biomedical applications.

Keywords: *Magnesium, Magnesium alloys, Magnesium composites, Applications, Engineering, Biomedical*

1 Introduction

Magnesium is the eight most abundant element (~2.5%) in earth's crust. Combined with its excellent recycling potential, Mg becomes an ideal candidate for sustainable applications. In natural state, Mg exists as carbonate in magnesite ($MgCO_3$), dolomite ($MgCO_3 \cdot CaCO_3$), hydroxide in brucite $Mg(OH)_2$, chloride in carnallite $KCl \cdot MgCl_{2 \cdot 6}(H_2O)$, and sulphate in kieserite $MgSO_4 \cdot H_2O$. Given the abundant availability of Mg as dissolved chlorides in sea water (0.13%), the industrial production of Mg was achieved through the electrolysis of molten $MgCl_2$. Today, the commercial production of Mg also involves thermal reduction of mineral ore through the Pidgeon process[1,2].

With a density of ~1.74 g/cc, i.e., ~35% lighter than Al and ~75% lighter than steel, Mg exhibits comparable properties as aluminium, as shown in Table 1. Other salient properties of Mg include excellent castability, machinability, damping capacity, heat dissipation, and electromagnetic shielding characteristics[3]. Being the most reactive of all structural metals, it reacts strongly with oxygen and ignites easily in dry air when present in powdered form. The high reactivity of Mg together with its weight saving attribute was exploited in the past for making explosives, pyrotechnic devices, and rocket propellants for military applications during World War II. In recent times, applications of Mg materials for various commercial sectors have been widened via the development of its wrought products, photoengraving technology, and surface treatment systems[4].

2 Development of Magnesium Alloys

Despite the various advantages of Mg, its use in the pure form is rather limited due to the issues such as flammability, low corrosion resistance, and inadequate mechanical properties. While its

Damping capacity: material's ability to dissipate elastic strain energy during mechanical vibration or wave propagation.

Electro-magnetic shielding: Practice of blocking the electromagnetic field by using barriers made of conductive or magnetic materials.

Pyrotechnic device: A fireable mechanical device on spaceship used for separating the spacecraft and rocket, releasing instrument covers, boom (swing arm) or parachutes, and jettisoning the aeroshell.

Electrolysis: process by which the mineral ores are broken down into simpler ions using electric current.

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Table 1: Properties of magnesium and aluminium[1].

Properties	Magnesium	Aluminium
Atomic number	12	13
Atomic weight	24.32	26.98
Crystal structure	HCP	FCC
Density	1.74	2.70
Melting point	650	660
Boiling point	1105	2520
Thermal expansion coefficient (μm/mK)	25.5	23.6
Elastic modulus (GPa)	45	69
Tensile strength (MPa)	240	320
Specific strength (kNm/kg)	35–260	7–200
Specific stiffness (MNm/kg)	21–29	25–38

ability to corrode in aqueous solution is useful for cathodic protection in batteries, structural applications require corrosion resistance. Regarding this mechanical properties, pure Mg has poor ductility and low strength loss due to the inherent paucity of slip systems in the HCP crystal structure which can be overcome by the right selection of alloying elements[5].

Aluminium (Al) and Zinc (Zn) are the commonly used alloying elements, as they improve the strength, hardness, and castability of Mg. In general, zinc addition is usually limited to less than 2% to prevent hot shortness. On the other hand, Mg–Al alloys become heat treatable when the Al content is more than 6%. While the combined addition of Al and Zn helps to overcome the harmful corrosive effects of iron and nickel impurities, the addition of Zn in combination with Zirconium (Zr) and rare-earth (RE) metals produce precipitation hardened alloys with good strengths. Zr is an effective grain refiner for Mg as its lattice parameters are close to those of Mg ($a_{Zr} = 0.323$ nm, $c_{Zr} = 0.514$ nm, $a_{Mg} = 0.320$ nm, $c_{Mg} = 0.520$ nm). However, the combined addition of Zr and Al is not recommended because of their tendencies to form stable phases. RE elements, in general, improve the ductility, high-temperature creep resistance, and corrosion resistance of Mg. They also facilitate elimination of porosities in cast Mg-alloys as they narrow down the metal freezing range of the alloys. In particular, yttrium with high solid solubility in Mg (12.4%) improves the creep resistance, thermal stability, corrosion resistance, and its deformation behavior (better ductility and work hardening) of wrought Mg–Y alloys when added together with other RE elements such as cerium or neodymium. Similarly, thorium and strontium addition are also useful to improve the creep performance of Mg-alloys.

Addition of tin improves the fluidity of Mg melt and reduces the cracking tendency during hot working. Similarly, silicon (Si) addition also increases the fluidity of molten Mg. However, Si reduces corrosion resistance of Mg. Copper addition more than 0.05% also adversely affects the corrosion resistance of Mg, although the room temperature and high-temperature strengths are improved. In this regard, manganese addition in small quantities eliminates impurities like iron and nickel that are detrimental for the corrosion performance of Mg-alloys.

Lithium (Li) with extremely low density (0.54 g/cc) and high solid solubility is an attractive alloying element for developing lightweight Mg-alloys. The excess addition of lithium (> 11.5%) improves the formability of Mg-alloys by changing the crystal structure from HCP to BCC. However, lithium addition negatively affects the flammability and strength of Mg-alloys. In this regard, calcium (Ca) addition is also beneficial for light weighting and oxidation control. While Ca improves rollability of Mg sheets, excess calcium leads to cracking during the welding process. Being a major component of human bone, calcium addition is also beneficial for developing biomedical Mg-alloys. Addition of silver (Ag) is also beneficial for biomedical applications as it improves the antibacterial properties and biocompatibility of Mg-alloys. Ag also improves the mechanical properties by age-hardening[1,5–8].

According to American Society for Testing and Materials (ASTM), Mg-alloys are named using a standard four-part naming system highlighting

Cathodic protection: Technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell.

Hot working: Processes where metals are plastically deformed above their recrystallisation temperature.

Slip systems: Set of symmetrically identical slip planes and associated family of slip directions for which the dislocation motion can easily occur and lead to plastic deformation.

HCP: Hexagonal closed pack.

Hot shortness: Type of solidification defect characterized by cracking of material along its grain boundaries upon cooling.

BCC: Body centred cubic.

Age-hardening: Also known as precipitation hardening, is a type of heat treatment that make use of solid impurities or precipitates for the strengthening process.

Table 2: ASTM designation of Mg-alloys[1].

Part 1	Part 2	Part 3	Part 4
Major alloying constituents	Amounts of major alloying constituents	Alloy version to distinguish between different alloys with same quantity of major alloying additions	Temper condition
Two alphabets	Two numbers	One alphabet (except I and O)	one alphabet followed by a number
Aluminium (A) Zinc (Z) Zirconium (K) Rare earth (E) Yttrium (W) Thorium (H) Strontium (J) Tin (T) Silicon (S) Copper (C) Manganese (M) Lithium (L) Calcium (X) Silver (Q)			As fabricated (F) Annealed (O) Strain hardened (H1) Strain hardened and partially annealed (H2) Strain hardened and stabilized (H3) Solution heat treated at room temperature (W) Thermally treated, cooled and natural aged (T1) Solution heat treated and cold worked (T3) Solution heat treated (T4) Cooled and artificially aged only (T5) Solution heat treated and artificially aged (T6) Solution heat treated and stabilized (T7) Solution heat treated, cold worked, and artificially aged (T8) Solution heat treated, artificially aged, and cold worked (T9) cooled, artificially aged, and cold worked (T10)

the major alloying elements, its composition, development progress, and the temper condition, as shown in Table 2. For example, in AZ81A-T4, the first section consists of two letters 'A' and 'Z' representing the major alloying elements, aluminium and zinc. The second part consists of two numbers '8' and '1' indicating the amount of major alloying additions (i.e., 8% Al and 1% Zn). The third part consists of a letter highlighting the version of alloy, i.e., 'A' indicates it as the first alloy version with approximately 8% Al and 1% Zn. The fourth part, T4, indicates its temper condition as solution treated.

Mg-alloys can be broadly classified as cast alloys and wrought alloys[1,5,6]. In cast Mg-alloys, Mg–Al alloys form the major group. While the AZ series alloys with Al and Zn alloying additions have adequate room-temperature mechanical strength, their high-temperature properties are usually inferior. AM series alloys containing minor Mn content without Zn exhibit higher toughness and ductility in addition to salt-water corrosion resistance. For high-temperature and creep requirements, AS, AE, and AJ series alloys developed using silicon, rare earths, and strontium alloying additions are recommended as they promote the formation of thermally stable intermetallics with Al. In case of Al-free Mg-alloys, the ZK, ZE, WE, and QE series alloys with zinc, rare earths, and silver additions in combination with minor zirconium are ideal for low- and medium-temperature applications. While these alloys exhibit better strength due to grain refinement obtained by Zr addition and heat treatment, ZK and ZE series alloys are susceptible to hot shortness due to larger amounts of Zn addition. Thorium-added HK and HM series alloys also exhibit superior mechanical properties, such as high strength and creep resistance. However, they are limited to defence applications such as missile construction due to thorium's radioactivity. Recent works report on heat treatment methods to develop ultra-high-strength Mg-alloys containing very fine nanostructured precipitates and ordered phases[8,9].

While the cast alloys are produced directly using die and other casting methods, wrought alloys involve secondary metal forming such a rolling, forging, and extrusion at temperatures more than 300 °C[10]. Due to grain refinement and

Grain refinement: Method of strengthening materials by changing their average crystallite (grain) size.

Mechanical anisotropy: Directionally dependent mechanical properties

Orowan strengthening: Also known as dislocation bowing, refers to the strengthening of materials by precipitates that are strong enough to resist dislocation penetration.

extensive plastic deformation, wrought alloys usually have superior strength compared to cast alloys. The wrought processing of Mg-alloys develops a strong fibre texture that causes mechanical anisotropy and poor ductility. RE additions are considered as beneficial for ductility enhancement due to weakening of fibre texture[11]. Alloying addition of strontium also produces a two-component texture for formability improvement[12]. Li also improves the formability of wrought Mg-alloys as it reduces the axial ratio (c/a) of HCP-Mg and facilitates activation of non-basal prismatic planes[13]. While lithium addition > 11.5 wt.% completely transforms the crystal structure into BCC, lithium addition between 5.5 to 11.5 wt.% results in duplex (HCP + BCC) structure. Recently, severe plastic deformation (SPD) methods like equal channel angular processing (ECAP) are also being used to produce ultra-fine-grained, texture-free Mg-alloys with exceptional strength and ductility[14]. Table 3 shows the properties of commercial Mg-alloys.

3 Magnesium-Based Metal Matrix Composites

In addition to strength improvement by alloying, the mechanical properties of Mg can be improved by the incorporation of hard and strong ceramic reinforcements in the form of fibres and particles, i.e., by making magnesium metal matrix composites (Mg MMCs). The properties of MMCs depend on multiple factors such as the strength and stiffness of reinforcement, its compatibility and dispersion in Mg-matrix, and the interfacial integrity. Therefore, reinforcement materials with the following properties are selected to make Mg-composites: (i) low density, (ii) good interfacial bonding, (iii) good wettability, (iv) high hardness and strength, (v) considerable difference in coefficient of thermal expansion (CTE) value for better strengthening, (vi) low corrosion, and (vii) easy availability and cost effectiveness.

The choice of reinforcement also depends on the type of matrix material and manufacturing methods. Table 4 lists the properties of common reinforcements to develop Mg-composites. Most reinforcements improve the strength and wear resistance of Mg-alloys. While the properties of fibre-reinforced composites depend on the orientation of fibres and loading direction, particle reinforcements offer isotropic properties. Table 5 lists the properties of Mg MMCs highlighting the strengthening capabilities of ceramic particle reinforcement.

Addition of particle reinforcement improves the strength and stiffness of Mg-matrix by (i) effective load transfer from soft Mg-matrix to hard and strong reinforcements, (ii) residual stress due to thermal cycling, (iii) enhanced dislocation density due to difference in CTE and modulus between Mg-matrix and reinforcing phases, (iv) grain size strengthening due to grain refinement, and (v) Orowan strengthening due to resistance to dislocation motion by the hard reinforcement particles[27,28]. Addition of nano-sized particle reinforcement in small amounts (< 5 vol%) produces similar or superior strengthening effect when compared to larger amounts of micron-sized particles (Fig. 1)[29–31]. In micron-sized particle-reinforced MMCs, the weak particle–matrix interface along with particle cracking results in their premature failure and poor ductility, and hence is only effective for strength improvement at the expense of ductility. In contrast, in nano-sized particle-reinforced MMCs, the effective dispersion of nano-reinforcements contributes to strengthening without any adverse effects on ductility (Table 5)[29–31]. Therefore, nanoparticles have received substantial research attention as reinforcement to improve the mechanical properties of Mg. Published literature on Mg-nano-composites highlights combined addition of more than one type of reinforcement to derive multiple benefits[32]. Such hybrid composites are ideal for property optimisation including control of local microstructure, wettability enhancement, efficient load transfer, and sharing.

Particle reinforcement improves wear resistance of Mg materials. The reduced wear rate of Mg-composites can be directly related to the increase in reinforcement content and hardness as per Archard's wear equation ($Q = kW/H$, where Q is the volume worn per unit sliding distance, W the applied load, H the hardness, and k the wear coefficient)[43]. The wear mechanism changes with respect to the size of reinforcement particles. While the addition of micron-sized reinforcement particles in larger amounts causes an increase in friction and wear by delamination, the lower volume fraction along with smaller (nano) particle size does not induce severe friction and counter abrasion[44]. In particular, the strain mismatch between Mg-matrix and micro-sized particles causes a variation in the stress distribution at the particle matrix interface resulting in particle debonding and pull out. Mg-nano-composites undergo wear by abrasion, adhesion, and oxide layer formation instead of prominent delamination[31,44].

Table 3: Properties of cast and wrought Mg-alloys[1,3,4,16].

Alloy	Density (g/cc)	Process	(Temper)	Tensile strength (MPa)	Yield strength (MPa)	Elon-gation (%)
AZ31B (Al: 2.5–3.5%; Zn: 0.6–1.4%; Mn: 0.2% min)	1.77	Extrusion	(F)	260	200	15
			(T4)	255	150	21
		Sheets	(T6)	290	220	15
		Forging	(F)	260	195	9
AZ61A (Al: 2.5–3.5%; Zn: 0.6–1.4%; Mn: 0.2% min)	1.77	Extrusion	(F)	310	230	16
		Forging	(F)	195	180	12
AZ63 (Al: 6%, Zn: 3%, Si: 0.3, Mn: 0.1%)	1.83	Sand casting	(F)	200	97	6
			(T4)	275	97	12
			(T5)	200	105	4
			(T6)	275	130	5
AZ80A (Al: 7.8–9.2%; Zn: 0.2–0.8%; Mn: 0.12% min)	1.8	Extrusion	(F)	340	250	11
			(T5)	380	275	7
		Forging	(F)	315	215	8
			(T5)	345	235	5
			(T6)	345	250	5
AZ81 (Al: 7.6%, Zn: 0.7%, Mn: 0.13%)	1.8	Sand casting	(T4)	275	85	15
AZ91A, B, D (Al: 9%, Zn: 0.7%, Mn: 0.3%)	1.81	Sand casting	(F)	185	150	3
			(T4	250	80	4.5
			(T6)	230	130	2.3
AZ91C, E (Al: 9%, Zn: 0.7%, Mn: 0.3%)	1.81	Sand casting	(F)	165	95	-
			(T4)	275	85	-
			(T6)	275	195	-
AS21 (Al: 2.2%, Si: 1%, Mn: 0.1%)	1.78	Die casting	(F)	220	120	7
AS41A, B (Al: 4.25%, Mn: 0.35%)	1.78	Die casting	(F)	240	140	8
AE42 (Al: 4%, RE: 2.4%, Mn: 0.25%)	1.79	Die casting	(F)	230	145	6
AE44 (Al: 4%, RE: 4%)	1.82	High-pressure die casting	(F)	245	142	10
AJ62 (Al: 6%, Sr: 2.4%)	1.8	High-pressure die casting	(F)	240	143	3
AM20 (Al: 2%, Zn: 0.2%, Mn: 0.2%, Si: 0.05%)	1.75	Die casting	(F)	210	90	20
AM50 (Al: 5%, Mn: 0.35%)	1.77	Die casting	(F)	230	125	8
AM60A, B (Al: 6%, Mn: 0.3%)	1.8	Die casting	(F)	220	130	6
AM100A (Al: 10%, Mn: 0.1%)	1.83	Sand casting	(F)	150	83	2
			(T6)	275	110	4
ZK51 (Zn: 4.5%, Zr: 0.7%)	1.83	Sand casting	(T5)	276	165	3
ZK60A (Zn: 4.8–6.2%; Zr: 0.45% min)	1.83	Extrusion	(F)	340	250	14
			(T5)	365	305	11
		Forging	(T5)	305	260	16
			(T6)	325	270	11
ZE41 (Zn: 4.2%, RE: 1.2%, Zr: 0.7%)	1.84	Sand casting	(T5)	205	140	3.5

Table 3: (continued)

Alloy	Density (g/cc)	Process	(Temper)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
ZE33 (Nd: 3.5%, Zr: 0.7%)	1.8	Sand casting	(T5)	160	105	3
ZE63 (Zn: 5.7%, RE: 2.5%, Zr: 0.7%)	1.87	Sand casting	(T6)	295	190	7
WE43 (Y: 4.75%, Nd: 3%, Zr: 0.7%, Zn: 0.2%)	1.8	Sand casting	(T6)	235	190	4
WE54 (Y: 5.25%, RE: 1.75%, Nd: 1.75)	1.8	Sand casting	(T6)	270	190	4
EQ21 (Nd: 2.5%, Ag: 1.5%, Zr: 0.7%)	1.81	Sand casting	(T6)	234	172	2
QE22 (Ag: 2.5%, RE: 2%, Zr: 0.6%)	1.81	Sand casting	(T6)	275	205	4
ZC63 (Zn: 6.5%, Cu: 3%, Mn: 0.75%)	1.87	Sand casting	(T6)	210	125	4
ZC71 (Zn: 6–7%; Cu: 1–1.5%; Mn: 0.5–1%)	1.83	Extrusion	(F)	360	340	5
HM31 (Th: 2.5–3.5%; Mn: 1.2% min)	1.8	Extrusion	(F)	290	230	10
			(T5)	300	270	10
HK31A (Th: 2.5–3.5%; Mn: 1.2% min)	1.8	Sheets	(T6)	255	200	9

Table 4: Properties of common reinforcement materials[16].

Material	Crystal structure	Density (g/cc)	Melting point (°C)	Thermal conductivity (W/mK)	Thermal expansion coefficient (μm/mK)	Modulus GPa
Al_2O3	Hexagonal closed pack	3.9	2050	25	8.3	410
AlN	Hexagonal closed pack	3.25	2300	10	6	350
B_4C	Rhombohedral	2.52	2450	29	5–6	450
BN	Hexagonal closed pack	2.2	3000	25	3.8	90
SiC	Hexagonal closed pack	3.21	2300	59	4.7–5	480
Si_3N_4	α-Trigonal β-Hexagonal closed pack γ-Cubic	3.29	1900	29	3.3	310
TiB_2	Hexagonal closed pack	4.5	2900	27	7.4	370
TiC	Cubic	4.93	3140	29	7.4	320
TiN	Cubic	5.24	2950	29	9.4	600
WC	Hexagonal closed pack	15.7	2800	110	5.2	690

4 Corrosion of Magnesium-Based Materials

The mechanism of corrosion in metallic materials depends on multiple factors such as corrosion medium, composition, microstructure features (e.g., presence of grain boundary precipitates and elemental segregation), and surface film properties. Due to its low electrochemical potential, Mg undergoes severe galvanic corrosion when in contact with other relatively noble metals and ceramics[45]. Wet corrosion of magnesium in aqueous medium involves the formation of $Mg(OH)_2$ as shown below

Anodic reaction: $Mg \rightarrow Mg^{2+} + 2e^-$

Cathodic reaction:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Table 5: Tensile properties of pure Mg-based MMCs reinforced with ceramic reinforcements.

Reinforcement	Reinforcement size (μm)	Vol. (%)	Processing method[a]	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Reference
Al_2O_3	1	1.1	PM + HE	227	172	16.8	[17]
	0.3	1.1		237	182	12.1	
	0.3	0	MWS-PM + HE	168	117	2.8	[18]
		5		215	160	3.9	
		2.5		167	130	4	
	0.3	0.7	DMD + HE	261	214	12.5	[19]
		1.1		251	200	8.6	
		2.5		281	222	4.5	
	0.05	0	PM + HE	193	132	4.2	[20]
		0.22		232	169	6.5	
		0.66		247	191	8.8	
		1.11		250	194	6.9	
		0	DMD + HE	173	97	7.4	
		0.22		207	146	8	
		0.66		229	170	12.4	
		1.11		246	175	14	
SiC	0.5–25	0	SPS + HE		115		[21]
		5			130		
		10			140		
		15			120		
	25	0	DC	199	110	10.2	[22]
		4.3		191	112	6.8	
		8.7		177	112	4.7	
		16.8		154	114	1.8	
	40	30	SC	258	229	2	[23]
	0.6	0	DMD + HE	207	153	9.2	[24]
		2.7		219	182	2.1	
		5.8		221	171	1.5	
		9		207	155	1.4	
	35	0	DMD + HE	219	153	3.1	[25]
		33.6		205	158	12.1	
	0.05	0	MWS-PM + HE	172	125	5.8	[26]
		0.35		194	132	6.3	
		0.5		194	144	7	
		1		203	157	7.6	

[a] DC: die casting; DMD: disintegrated melt deposition; HE: hot extrusion; PM: powder metallurgy; MWS-PM: microwave sintering-assisted powder metallurgy; SC: stir casting; SPS: spark plasma sintering

Product formation:

$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2$.

Combined with the poor stability of $Mg(OH)_2$ films, the continued releases of Mg^{2+} anions cause excessive loss of material by chloride formation when exposed to chloride ions as shown below. Similarly, the segregation of grain boundary phases and reinforcements also results in intergranular corrosion[46]. While the evolution of hydrogen gas declines the rate of degradation, the weak nature of protective oxide film results in faster degradation

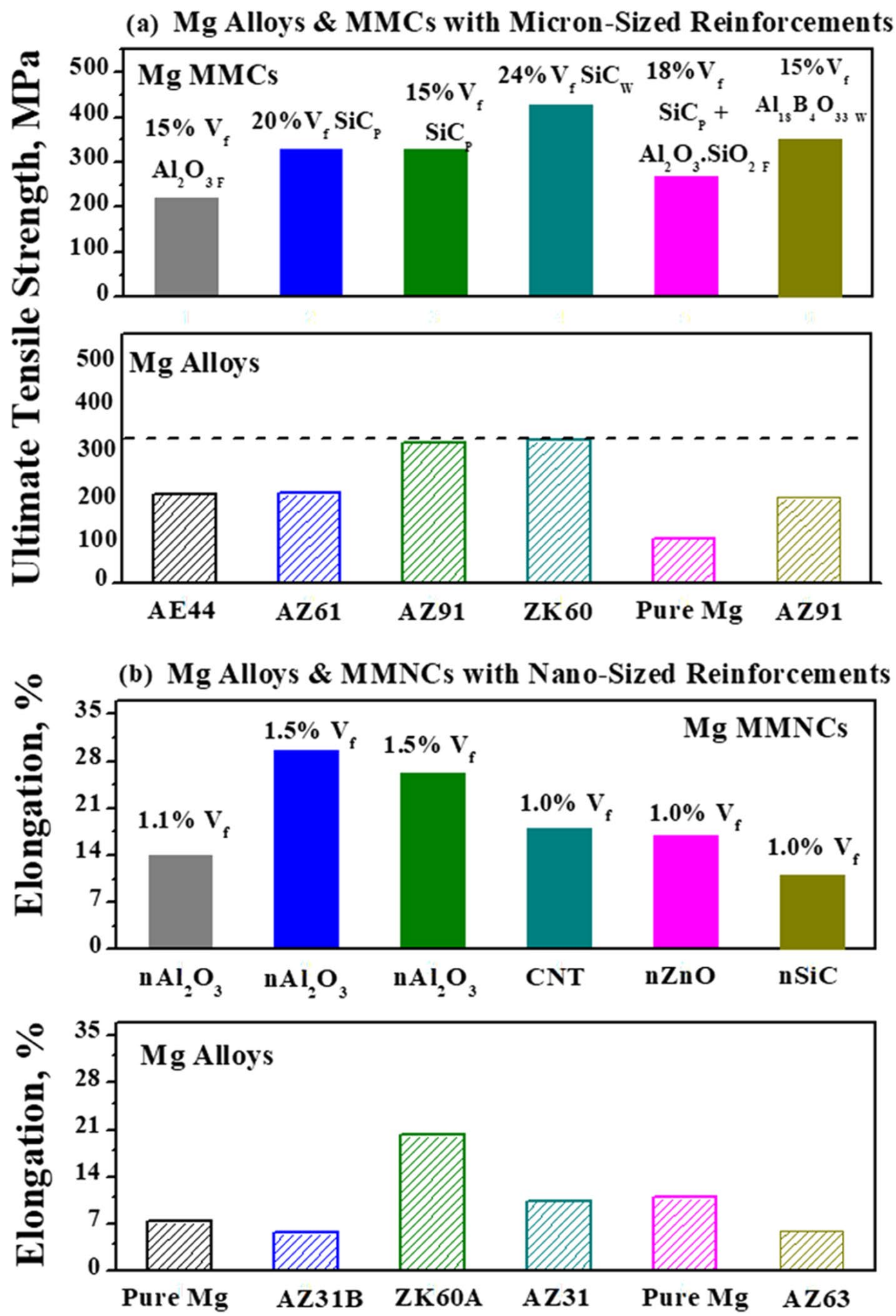

Figure 1: Mechanical properties of Mg-based metal matrix composites[28,33–42].

Anodic reaction: $Mg \rightarrow Mg^{2+} + 2e^-$

Cathodic reaction: $Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$

Product formation: $Mg(OH)_2 + 2Cl^- \rightarrow MgCl_2$

Product formation: $Mg^{2+} + 2Cl^- \rightarrow MgCl_2$.

Biodegradability of Mg makes it suitable for temporary implant applications[47]. Furthermore, the properties of Mg match closely with that of human bone as shown below (Table 6). However, faster degradation of Mg in body fluids combined with toxicity risks from alloying additions and reinforcement necessitates extensive research on the biocorrosion and cytotoxicity attributes of Mg materials. While the addition of Zr, Mn, and RE improves the corrosion resistance of Mg, alloying elements such as Ca, Mn, Zn, and Ag are beneficial in retaining the biocompatibility of Mg

Biocompatibility: Describes the property of a material being compatible with living tissue.

Table 6: Properties of implant materials[47].

Material	Density (g/cc)	Elastic modulus (GPa)	Compressive yield strength (MPa)
Cortical bone	1.6–2.0	5–23	164–240
Cancellous bone	1.0–1.4	0.01–1.5	–
Ti6Al4V	4.5	114	–
Synthetic HA	3.05–3.15	70–120	100–900
DL-PLA	–	1.9–2.4	–
Cast magnesium	1.74	41	
Die cast AZ91D	1.81	45	160
Extruded AZ31	1.78	45	60–70
Extruded WE43 T5	1.84	44	–
Stainless steel	7.7	189–205	170–310

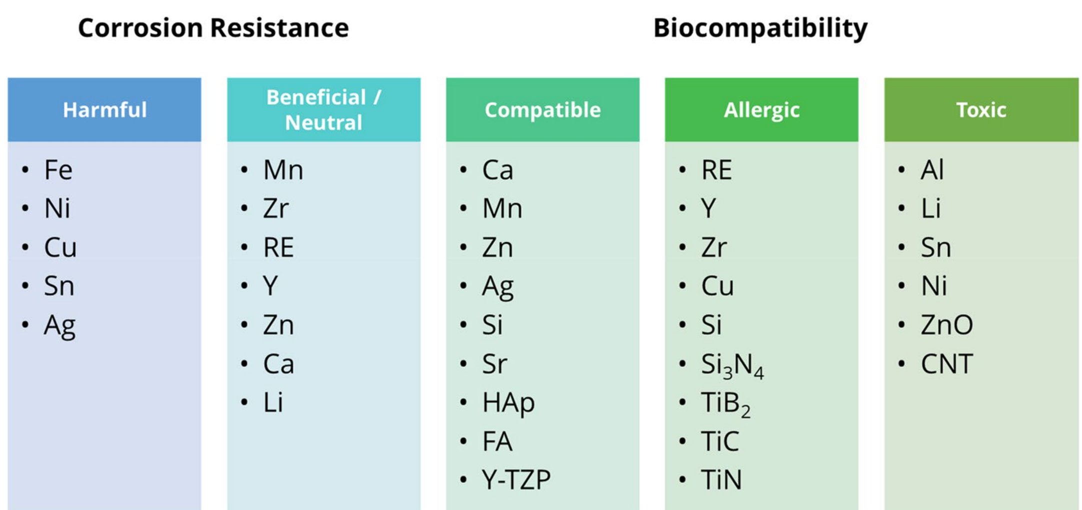

Figure 2: Effects of alloying additions and reinforcement on the corrosion resistance and biocompatibility of Mg.

(Fig. 2). In general, particle reinforcements increase the galvanic corrosion in Mg. However, recent studies establish the benefits of nano-sized reinforcements as they can improve the surface chemical activity and promote the formation of protective surface films. The actual benefits depend on the type of reinforcement and processing methods.

5 Processing of Mg-Based Materials

A variety of processing methods are used to produce Mg-based materials which are broadly classified into: (i) solid-phase processing and (ii) liquid-phase processing. Processing method should be selected, such that it can produce materials with homogeneously distributed reinforcement particulates, which is essential to achieve desired mechanical properties[30].

Solid-phase processes based on blend-press-sinter and mechanical alloying methods yield better strength properties due to less segregation and minimal brittle interfacial reaction products[48]. Blend-press-sinter technique is a solid-state processing method which involves blending or mixing of raw materials in powder form, followed by compaction and sintering. In some cases, the powder materials are also subjected to reactive ball milling that involves repeated cold welding, fracturing, and re-welding of powder particles in a high-energy ball mill. While the frictional heat developed at the particle interface results in local melting and consolidation of the powder particles, the rapid heat extraction by the cooler particle interior causes rapid solidification. Mechanical alloying can be used to synthesize a variety of high-strength equilibrium and non-equilibrium alloys/composites due to the high dislocation density and homogenous distribution of reinforcing constituents. Recent works report powder-based additive manufacturing techniques for the processing of Mg materials[49].

Compared to solid-state processing, liquid-phase processing methods such as sand casting, gravity or pressure die casting, stir casting, and melt infiltration are economical for large quantity production of Mg materials[30]. These methods involve melting of selected raw material followed by pouring and solidification in a mould. The limitations of melt processing methods include the need of protective gases, formation of defects such as shrinkage and porosity, and difficulty in producing complex-shaped components. Spray deposition is also a liquid-phase processing method in which the molten metal is sprayed or deposited onto a substrate[50]. While high solidification rates and fine grain microstructure are the major advantages, spray deposition is often not economical due to excessive material wastage and residual porosity. A similar method, disintegrated melt deposition (DMD) inherits the combined benefits of stir casting, spray forming, and gravity die casting to offer fine grain structure[30,51]. In addition to primary processing methods as described above, secondary processing methods such as rolling, forging, and extrusion are used to produce wrought Mg materials[10].

To join Mg materials, a range of welding operations are used such as spot welding, seam welding, resistance welding, gas metal arc welding (MIG or GMAW), gas tungsten arc welding (TIG or GTAW), laser welding, or electron beam welding[52]. Fusion welding of Mg die castings is challenging due to the presence of porosity and brittle intermetallic phases. Solid-state welding methods such as magnetic pulse welding and friction stir welding are useful to achieve good weld quality[53]. Magnetic welding depends on the electromagnetic pulse, the frictional heat generated by a rotating tool used in friction stir welding. These methods minimize the formation of brittle intermetallics and are also useful in joining Mg with dissimilar metals including aluminium and steel. Adhesive bonding is also used to join Mg materials, although it requires extensive surface preparation to overcome corrosion and oxidation issues.

6 Applications of Magnesium-Based Materials

6.1 Aerospace Applications

Being lightweight, Mg-based materials are ideal materials for structural weight reduction in transportation sector. Currently, most aircraft manufacturers including Airbus, Boeing, and Embraer have limited the use of Mg to non-structural applications because of the restrictions by Federal Aviation administration due to concerns associated with ignition and flammability. In the past, Mg was extensively used in military aircrafts and examples include B-36 aircraft bomber which contained 19,000 lbs of magnesium, Eurofighter Typhoon, Tornado, and F16. Other well-known examples of Mg applications in aircrafts include the main transmission of Sikorsky UH60 and S92, the auxiliary casing of F119, PW305 turbofan, and thrust reverser cascade in 737, 747, 757, and 767 aeroplanes. With FAA's ban being lifted recently, alloys such as Elektron 21 and WE43 are approved for the in-cabin usage in commercial aircrafts[54]. Space industry is also exploring the use of Mg to manufacture satellite components[55]. Figure 3 shows the current and potential aerospace applications of Mg materials.

6.2 Automobile Applications

In automobiles, Mg is predominantly used as sheets or engine blocks and components such as instrument panel, dashboard, steering wheel, components of steering wheel column, power trains, and transfer case, as shown in Fig. 4[56],[57]. However, use of Mg for critical engineering components and assemblies is restricted due to its poor corrosion resistance. Although the isolation of Mg parts would be effective to overcome galvanic corrosion, cost-effective coatings, and methods are required to realize the complete potential of Mg in automotive applications. Table 7 lists some of the current application examples of Mg materials in automobiles.

6.3 Electronic Applications

The lightweight and heat dissipation capabilities of Mg combined with damping, electromagnetic shielding, and recycling benefits promote its use in consumer electronics such as the casings for mobile phones, cameras, and laptops, as shown in Fig. 5[58]. Compared to lightweight plastics used in electronic packaging, Mg offers additional benefits in terms of electromagnetic shielding and recyclability. In particular, the composites containing particle reinforcements

Figure 3: Mg-based materials used in aerospace applications.

Figure 4: Mg-based materials used in automobiles.

were found to have superior electromagnetic shielding capabilities[59]. With respect to recyclability, Mg scrap can be fully recovered and recycled with only 5% of the energy needed to produce primary Mg-alloys[60]. In addition, Mg is also being considered as a medium for hydrogen storage applications[61].

6.4 Biomedical Applications

Mg has properties comparable to those of human bone and is hence ideal for making bone implants as they tend to reduce the stress shielding effects unlike other implant materials such as Ti or steels that have extremely high elastic modulus[47,62,63]. Its natural degradation in the human body together with biocompatibility eliminates the

Table 7: Examples of Mg-alloy applications in automobiles[56].

Component	Car models
Engine and transmission parts	
Engine block	BMW (N52), Ford, Porsche (911)
Intake manifold	BMW (V8 motor), GM (V8 North Star motor), Chrysler
Lower crankcase	Chrysler (Jeep), Alfa Romeo (GTV), GM (Oldsmobile), McLaren Motors (F1–V12)
Transmission case	AutoZAZ-Daewoo (Tavria, Slavuta, Daewoo-Sens), Volvo Motors (LCP), Porshe AG (911 series), Volkswagen (Volkswagen Passat), Audi (A4, A6), Mercedes-Benz, Ford (Bronco, Aerostar 1994)
Gearbox and controls housing	AutoZAZ-Daewoo (Tavria, Slavuta, Daewoo-Sens)
Cylinder block	GM (Pontiac Gran AM, Corvette)
Cylinder head	Dodge (Dodge Raw), Honda Motors (City Turbo), Alfa Romeo (GTV), AutoZAZ-Daewoo (Tavria, Slavuta, Daewoo-Sens), Honda, BMW, Ford, Isusu, Volvo Motors (LCP), Chrysler
Camshaft drive chain case (AZ91D)	Porsche AG (911 series), Chrysler (Jeep 1993, Viper)
Clutch case (AZ91B, AZ91D, AZ91HP)	Alfa Romeo (GTV), AutoZAZ-Daewoo (Tavria, Slavuta, Daewoo-Sens), Volvo Motors (LCP), Ford (Ranger), GM (Corvette)
Oil pan and pump housing	Ford (Ranger), Chrysler (Jeep), Chrysler (Viper), McLaren Motors (F1–V12)
Engine cradle	Ford, GM (Corvette)
Brackets (brake pedal, clutch, and accelerator)	Ford, GM, Chrysler
Interior parts	
Steering wheel frame	Ford (Thunderbird, Cougar, Taurus, Sable, Ranger), Chrysler (Chrysler Plymouth, LH Midsize 1993), Toyota, BMW (MINI), Lexus (Lexus LS430), GM (Oldsmobile, Pontiac, Buick)
Steering link bracing	GM (LH Midsize)
Instrument panel	GM, Chrysler (Jeep), Ford, Audi (A8), Toyota (Toyota Century)
Seat frame	GM (Impact), Mercedes-Benz (Mercedes Roadster 300/400/500 SL), Lexus (Lexus LS430)
Brake and clutch pedal	GM Oldsmobile, Pontiac, Buick
Door inner	Aston Martin (DB9 2004)
Console bracket	Ford
Air bag retainer	Chrysler
Chassis components	
Wheel rims	Toyota (Toyota 2000GT, Toyota Supra), Alfa Romeo (GTV), Porshe AG (944 and 911)
Lift gate	Chrysler (Pacifica 2017), Lincoln (MKT Luxury Crossover 2010), Mercedes (E-Class T-Model 2009), Aston Martin (Vanquish S 2017)
Valve cover	GM (Corvette)
ABS mounting bracket	Ford, Chrysler

need for corrective surgery, thereby reducing the risk of multiple surgeries and associated heath care costs. Being a nutrient required for enzyme reactions and metabolic processes, Mg released into human body upon degradation is well tolerated by the human biosystem. Recent research works confirm the healing and bone formation potential of Mg implants[64]. Furthermore, the excellent machinability of Mg also facilitates the machining of implants with intricate shapes and size. Currently used bone implants include bone screws, pins, surgical plates, clips, sutures, and wires. Other than bone implants, resorbable scaffolds made of Mg are also being explored for coronary vascular intervention. Figure 6 shows a few examples of Mg-based materials used in biomedical applications.

As seen in Figs. 3, 4, 5 and 6, Mg-alloys are being widely used in applications related to aerospace, automobiles, consumer electronics, and

Figure 5: Applications of Mg-based materials in consumer electronics.

biomedical sectors, both in the cast and wrought forms. However, Mg-composites with both micron-sized and nano-sized reinforcements are still in the development stage, with alumina and SiC being the widely researched reinforcements due to their ease of processing, availability, cost, and compatibility with most of the Mg-matrices.

In Mg-composites containing micron-sized reinforcements, despite having high strength, high-temperature stability, and wear resistance, their applications are restricted to cast components due to their limitation in ductility (Table 5; Fig. 1a). Mg–Al-based alloy matrices such as AZ31 and AZ91 have been widely explored under various loading conditions and superior properties have been observed when compared to the unreinforced alloys. The AZ alloy-based micron-sized reinforced composites (with Al_2O_3 and SiC reinforcements) can hence effectively replace most of the existing cast Mg-alloy components in automobiles and aerospace sectors. In particular, for enhanced creep resistance, currently Al-free Mg-alloys or Mg–Al-RE alloys are preferred, although they are relatively expensive than AZ alloys. Considering the enhanced thermal stability and excellent creep resistance of cast AZ-based composites with micron-sized reinforcements, these composites are better alternatives for power train applications[67].

The greatest advantage of Mg-composites with nano-sized reinforcements is their excellent ductility, which is much higher than the unreinforced Mg-alloys as well as micron-sized reinforced composites. Pure Mg is not suitable for engineering applications at large due to its low ductility. From Table 3 and Fig. 1b, it is noteworthy that by the incorporation of nano-reinforcements, the ductility of pure Mg is significantly improved. Given the absence of undesired interfacial reactions and low-volume fraction of nano-reinforcement used, pure Mg-based nano-composites that still remain unexplored can be considered for future applications in wrought components, for non-critical applications. In particular, Mg-nano-composites with nano-alumina are promising materials in (a) sports cycles and bikes that would provide light weight, higher damping, and maneuverability, (b) frames/chassis of consumer electronics, which require nominal strength with enhanced toughness, and (c) seat pedal assembly and arm support in aircraft seats that require formability. Incorporation of pure Mg with biocompatible nano-reinforcements such as hydroxyapatite and alloying elements such as Ca or Zn would make them suitable for biomedical implants. Nevertheless, the need to investigate other properties such as fatigue, wear, corrosion, and oxidation behavior is critical. This will better the understanding of their performance and will ensure wider applicability of Mg-nano-composites.

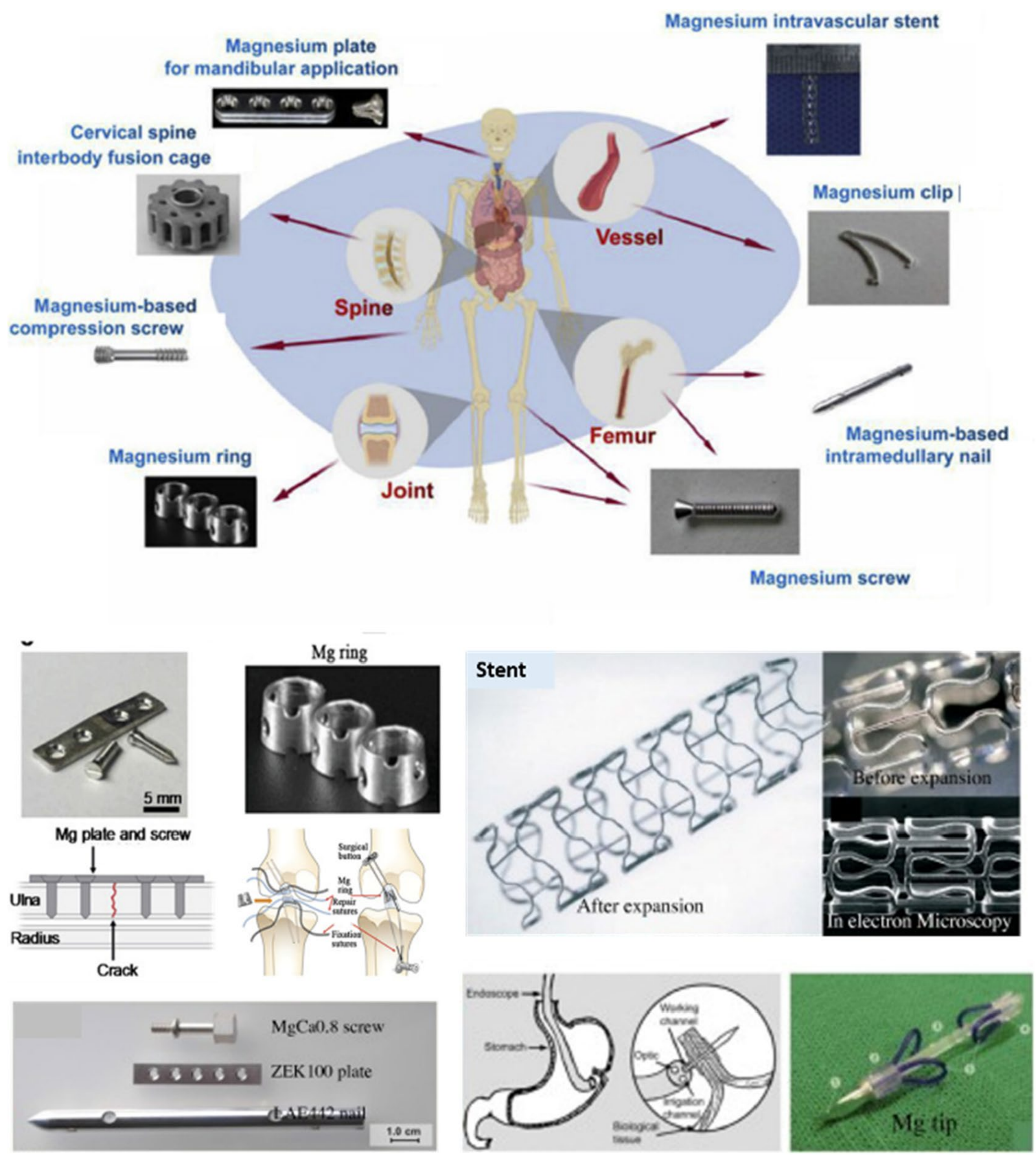

Figure 6: Mg-based materials in biomedical applications (from open access References[65,66]).

7 Concluding Remarks

Magnesium-based materials possess attractive properties such as low density, high strength-to-weight ratio, damping capacity, machinability, and biocompatibility. These properties make Mg materials attractive for various engineering and biomedical applications. Especially, the transportation sector aims to exploit its light weighting capabilities for fuel energy savings and emission control. In recent years, Mg materials are being considered for biomedical applications. However, some limitations of Mg materials include poor room-temperature formability, strength loss at elevated temperature, oxidation, corrosion, and flammability. Some of these issues are being addressed by development of new cast and wrought Mg-alloys. While most alloying additions are beneficial, superior properties can be realized using rare-earth additions. However, the non-availability of rare-earth metals makes then economically not viable. Research on use of low cost and nano-sized reinforcements and processing methods will contribute towards enhanced utilization of Mg materials and also for a wider spectrum of emerging applications.

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Declarations

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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