MAGNESIUM

THE LIGHTEST
STRUCTURAL METAL

International
Magnesium
Association

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International Magnesium Association

1000 Westgate Drive, Suite 252
Saint Paul, Minnesota 55114 USA
Phone: +1 651-379-7305
Fax: +1 651-290-2266
www.intlmag.org

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1. **Introduction**

Magnesium is the lightest structural metal and abundantly available in the earth's crust and seawater (the ninth most abundant element in the universe by mass). Magnesium is the third most commonly used structural metal, following steel and aluminum. With its density about one-fourth of steel and two-thirds of aluminum, magnesium provides excellent opportunities for lightweight applications in the transportation (land, air and sea), power-tools and 3C (computer, communication and consumer products) industries. Casting is one of the major manufacturing processes that can be used to produce magnesium components, and wrought magnesium products (extrusion, forging and sheet) are gaining more applications in recent years.

This brochure provides a concise summary of physical, chemical and mechanical properties of cast and wrought magnesium alloys for structural applications. The mass saving potentials of magnesium alloys are higher than other major structural materials such as mild steel, advanced high strength steel (AHSS), aluminum, polymers and polymer composites. The brochure also describes the general and galvanic corrosion properties of the most commonly used magnesium alloys. Protection measures against galvanic corrosion and surface finishing of magnesium products are also discussed.

2. **Pure Magnesium**

Magnesium is placed in the 2A series of the periodic table with an atomic number of 12. It has a hexagonal close packed (HCP) crystal structure and has a bright silver color. The physical and thermal properties of pure magnesium are presented in *Table 1*. The mechanical properties of pure magnesium depend on the processing route as shown in *Table 2*.

Table 1 – Physical properties of pure magnesium [1-4]

Property, Unit	**Value**
Density, g/cm^3	1.74
Melting point, °C	650
Boiling point, °C	1090
Volumetric shrinkage on solidification, %	4.2
Linear shrinkage, %	1.5
Solid linear shrinkage (650 – 20°C), %	1.7
Coefficient of thermal expansion (20 – 100 °C), µm. °C	26.1
Thermal conductivity (25°C), W/m.K	156
Electrical conductivity, S/m	2.3×10^7
Heat of fusion, kJ/mol	8.7
Heat of vaporization, kJ/mol	127.4

Table 2 – Mechanical properties of pure magnesium [4]

Condition	0.2% Yield stress, MPa	Ultimate tensile strength, MPa	Elongation, %	Hardness, HRB
Sand cast	21	90	2-6	30
Extrusion	69-105	165-205	5-8	35
Sheet - Hard rolled	115-140	180-220	2-10	45-47
Sheet - Annealed	90-105	160-195	3-15	40-41

3. Magnesium Alloys

Magnesium can be alloyed with many elements to enhance properties such as strength, castability, workability and corrosion resistance.

3.1 Alloy Designation

Each element added to magnesium is identified by a specific letter in the alloy designation. The notation as approved by American Society for Testing and Materials (ASTM) is presented in Table 3. The alloy designation contains two letters followed by two numbers. The first alphabet denotes the major alloying element and second alphabet identifies the second element. The numbers indicate the amount of the elements present in the alloy. For example, in alloy AZ91, "A" represents aluminum, the alloying element specified in the greatest amount; "Z" represents zinc, the alloying element specified in the second greatest amount; "9" indicates that the rounded mean aluminum percentage lies between 8.6 and 9.4; "1" signifies that the rounded mean of the zinc lies between 0.6 and 1.4.

The alloy can also have a letter following the four characters, usually A, B, C and so on. This final letter indicates the initial and subsequent developments of the particular alloy. Letter 'A' indicates that this is the first alloy whose composition qualified assignment of the designation AZ91. The letters B and C signify alloys subsequently developed whose specified compositions differ slightly from the first one and from one another, but do not differ sufficiently to effect a change in the basic designation.

Table 3 – Magnesium alloy designations

Letter	A	C	E	J	K	L	M	Q	S	T	V	W	Z
Element	Al	Cu	rare earth	Sr	Zr	Li	Mn	Ag	Si	Sn	Gd	Y	Zn

3.2 Cast Magnesium Alloys

Cast magnesium alloys often contain aluminum, manganese, zinc, silver or rare-earth elements as one of the major alloying additions. Other elements are added to improve specific properties. Aluminum is the major alloying element for common casting alloys made in sand, permanent mold and high-pressure die casting. High integrity castings for aerospace applications are made with other casting alloys based on silver, zinc and yttrium rather than aluminum. The advantage of these high integrity alloys is that they can be alloyed with zirconium to ensure a fine grain structure. The major alloying elements and cast magnesium alloy systems are presented in Table 4.

Table 4 – Casting magnesium alloys

Major alloying element	Alloy systems
Aluminum	AZ, AM, AJ, AE, AS
Zinc	ZE, ZK
Rare earth	EZ, EK, EQ, EV
Silver	QE
Yttrium	WE

Table 5 summarizes the compositions of some alloys used for gravity (sand and permanent mold) castings. The most common alloys for gravity casting are Mg-Al-Zn (AZ) and Mg-Al-Mn (AM) which have lower cost compared to Zr-containing alloys. However, these alloys including AZ91 (Mg-9%Al-1%Zn) offer limited mechanical properties and suffer from micro porosity in sand and gravity permanent mold castings. Zirconium is the most effective grain-refiner in Al-free magnesium alloys, often used in combination with other elements such as zinc, rare earths (cerium, gadolinium, neodymium), yttrium and silver. Alloys with zinc and rare earth elements (ZE or EZ systems) exhibit good high temperature strength and can be cast using sand or permanent mold processes. Silver was used extensively for many magnesium alloys (QE alloys) for aerospace applications due to the high temperature strength and castability, but due to poor corrosion resistance these alloys were largely replaced with newer ones containing yttrium (WE). The next generation aerospace alloy Elektron 21 (EV31A) was introduced to improve the castability compared with the WE43 alloy, and contains zinc, gadolinium and neodymium only.

Table 6 lists the composition of die cast alloys per ASTM standards. Similar to gravity cast alloys, there are currently two major alloy systems (AZ and AM) used for die casting applications. AZ91D is used for non-structural parts that are strength dominated and exposed to ambient temperatures like brackets, covers, cases and housings; providing essentially the same functionality with significant mass savings compared to steel, aluminum or zinc alloys. For structural applications such as instrument panels, steering systems and radiator supports, where fracture behaviour is important, AM50A (Mg-5%Al-0.3%Mn) or AM60B (Mg-6%Al-0.3%Mn), offer unique advantages due to their higher ductility (about 10% elongation) and higher impact strength compared to die cast A380 aluminum alloy. Other alloys such as Mg-Al-Sr (AJ), Mg-Al-RE (AE) and Mg-Al-Si (AS) were developed for elevated temperature applications.

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Tables 5 & 6 continue on next pages.

Table 5 - Chemical Requirements for Alloy Ingot for Remelt to Sand, Permanent Mold and Investment Castings—Composition % [5]

Alloy[A] ASTM	UNS	Mg	Al	Cu, max	Gd	Fe, max	Li	Mn	Nd	Ni, max	Rare Earths	Si, max	Ag	Y	Zn	Zr	Others each max[B]	Total Others, max[B]
AZ91E	M11918	remainder	8.3–9.2	0.015	...	0.005	...	0.17–0.50	...	0.0010	...	0.2	...	...	0.45–0.9	...	0.01	0.3
AZ92A	M11921	remainder	8.5–9.5	0.20	...	...	...	0.13–0.35	...	0.010	...	0.2	...	...	1.75–2.3	...	...	0.3
EQ21A	M18330	remainder	...	0.05–0.10	...	...	...	...	...	0.01	1.5[C]–3.0[E]	0.01	1.3–1.7	...	...	0.3–1.0	...	0.3
EV31A[D]	M12311	remainder	...	0.01	1.0–1.7	0.010	...	...	2.6–3.1	0.0020	0.4[E]	...	0.05 max	...	0.20–0.50	0.3-1.0	0.01	...
EZ33A	M12331	remainder	...	0.03	...	...	...	...	...	0.010	2.6–3.9[F]	0.01	...	...	2.0–3.0	0.3–1.0	...	0.3
K1A	M18011	remainder	...	0.03	...	...	...	...	...	0.010	...	0.01	...	...	...	0.3–1.0	...	0.3
QE22A	M18221	remainder	...	0.03	...	...	...	0.15 max	...	0.010	1.9–2.4[C]	0.01	2.0–3.0	...	0.2 max	0.3–1.0	...	0.3
WE43A	M18431	remainder	...	0.03	...	....	0.18	0.15 max	2.0–2.5	0.005	1.9[G]	0.01	...	3.7–4.3	0.20 max	0.3–1.0	...	0.3
WE43B	M18433	remainder	...	0.01	...	...	0.18	0.03 max	2.0–2.5	0.004	1.9[G]	...	...[H]	3.7–4.3	...[H]	0.3–1.0	0.01	...
WE54A	M18410	remainder	...	0.03	...	...	0.20	0.15 max	1.5–2.0	0.005	2.0[G]	0.01	...	4.75–5.5	0.20 max	0.3–1.0	...	0.3
ZC63A	M16331	remainder	...	2.4–3.00	...	...	...	0.25–0.75	...	0.001	...	0.20	...	...	5.5–6.5	...	...	0.3
ZE41A	M16411	remainder	...	0.03	...	...	...	0.15 max	...	0.010	1.0–1.75[F]	0.01	...	...	3.7–4.8	0.3–1.0	...	0.3
ZK51A	M16511	remainder	...	0.03	...	...	...	...	...	0.010	...	0.01	...	...	3.8–5.3	0.3–1.0	...	0.3
ZK61A	M16611	remainder	...	0.03	...	...	...	...	...	0.010	...	0.01	...	...	5.7–6.3	0.3–1.0	...	0.3

[A] These alloy designations were established in accordance with Practice B951. UNS designations were established in accordance with Practice E527.

[B] Includes listed elements for which no specific limit is shown.

[C] Rare earth elements are in the form of Didymium, not less than 70% Neodymium balance substantially Praseodymium.

[D] Alloy EV31A is a patented composition, suitable for elevated temperature applications. Interested parties are invited to submit information regarding the identification of alternatives to these compositions to ASTM International. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this specification. Users of this specification are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

[E] Other Rare Earths may also be present to a total maximum of 0.4%. These Rare Earths shall principally be Cerium, Lanthanum, and Praseodymium.

[F] Total Rare Earths (TRE) are principally a mixture of Cerium, Lanthanum, Neodymium, and Praseodymium. The Cerium content should not be less than 45% of TRE.

[G] Other Rare Earths shall be principally heavy rare earths, such as, Gadolinium, Dysprosium, Erbium, and Ytterbium. Other Rare Earths are derived from the Yttrium, typically 80%, and 20% heavy rare earths.

[H] Zinc + Silver shall be 0.15% max.

Table 6 - Chemical composition (wt.%) of magnesium alloys for die casting per ASTM B93/B91M-15 [5].

Alloy	Al	Mn	Rare Earth	Sr	Zn	Cu, max	Fe, max	Si	Ni, max	Be	Other Metallic impurities, max each[A]	Other Impurities, max
AS41B	3.7–4.8	0.35–0.6	...	...	0.1 max	0.015	0.0035	0.60–1.4	0.001	0.0005-0.0015	0.01	...
AM50A	4.5–5.3	0.28–0.50	...	...	0.2 max	0.008	0.004	0.08 max	0.001	0.0005-0.0015	0.01	...
AM60B	5.6–6.4	0.26–0.50	...	...	0.2 max	0.008	0.004	0.08 max	0.001	0.0005-0.0015	0.01	...
AZ91D	8.5–9.5	0.17–0.40	...	...	0.45–0.9	0.025	0.004	0.08 max	0.001	0.0005-0.0015	0.01	...
AJ52A	4.6–5.5	0.26–0.5	...	1.8–2.3	0.2 max	0.008	0.004	0.08 max	0.001	0.0005-0.0015	0.01	...
AJ62A	5.6–6.6	0.26–0.5	...	2.1–2.8	0.2 max	0.008	0.004	0.08	0.001	0.0005-0.0015	0.01	...
AS21A	1.9–2.5	0.2–0.6	...	...	0.2 max	0.008	0.004	0.7–1.2	0.001	0.0005-0.0015	0.01	...
AS21B	1.9–2.5	0.05–0.15	0.06–0.25	...	0.25 max	0.008	0.0035	0.7–1.2	0.001	0.0005-0.0015	0.01	...

[A] Includes listed elements for which no specific limit is shown.

3.3 Wrought Magnesium Alloys

Table 7 lists the nominal composition of magnesium extrusion alloys per ASTM, with AZ31 the most widely used in commercial applications. With higher aluminum contents, AZ61 and AZ80 offer higher strength than AZ31 alloy, but at much lower extrudability. WE43 and WE54 have exceptional high temperature strength and creep performance and can be used up to 260°C. The high-strength Zr-containing ZK40 and ZK60 were designed for applications in racing cars and bicycles, such as wheels and stems.

There are only two sheet magnesium alloys listed by ASTM (Table 8). AZ31 is a general-purpose alloy with good weldability, high strength, and good cold formability. ZE10 is a general purpose alloy with good weldability and does not require stress relief after welding. It has moderate strength and shows superior formability. There are also many special grades of wrought alloys produced by Magnesium Elektron (Table 9).

Table 7 - Chemical composition (wt.%) of magnesium extrusion alloys for per ASTM B107/B107M-13 [6]

Alloy	Al	Ca	Cu	Fe	Li	Mn	Nd	Ni	Rare Earth	Si	Y	Zr, min	Zn	Other Impurities – each	Total Other[A] Impurities
AZ31B	2.5–3.5	0.04	0.05	0.005		0.20–1.0		0.005		0.10		...	0.6–1.4		0.30
AZ61A	5.8–7.2	...	0.05	0.005		0.15-0.5		0.005		0.10		...	0.40-1.5		0.30
AZ80A	7.8–9.2	...	0.05	0.005		0.12-0.5		0.005		0.10		...	0.20-0.8		0.30
M1A	...	0.3	0.05	...		1.2-2.0		0.01		0.10		...	...		0.30
WE43B	...	...	0.02	0.01	0.2	0.03	2.0–2.5	0.005	1.9[C]	...	3.7–4.3	0.40–1.0	[D]	0.01	...
WE43C	-	-	0.02	0.005		0.03	2.0–2.5	0.002	0.3–1.0[E]	...	3.7–4.3	0.2–1.0	0.06	0.01	-
WE54A	...	...	0.03	...	0.2	0.03	1.5–2.0	0.005	2.0[C]	0.01	4.75–5.5	0.40–1.0	0.2	0.2	...
ZK40A	...	...	...	...		...		...		...		0.45	3.5–4.5		0.3
ZK60A	...	...	...	...		...		...				0.45	4.8-6.2		0.3

[A] Includes listed elements for which no specific limit is shown.

[B] Manganese minimum limit need not be met if iron is 0.005%, or less.

[C] Other rare earths shall be principally heavy rare earths, for example, Gadolinium, Dysprosium, Erbium, and Ytterbium. Other Rare Earths are derived from the Yttrium, typically 80% Yttrium 20% heavy rare earths.

[D] Zinc + Silver content shall not exceed 0.20 % in WE43B.

[E] Other rare earths are heavy rare earths, such as Gadolinium, Dysprosium, Erbium, Samarium, and Ytterbium. The total of Gadolinium + Dysprosium + Erbium shall be 0.3 to 1.0%. Samarium shall not exceed 0.04% and Ytterbium shall not exceed 0.02%

Table 8 - Chemical composition (wt.%) of magnesium sheet alloys for per ASTM B90/B90M-15 [7]

Alloy	Al	Ca	Cu	Fe	Rare Earth	Mn	Ni	Si	Zr, min	Zn	Other Impurities, each	Total Other[A] Impurities
AZ31B	2.5–3.5	0.04	0.05	0.005	…	0.20–1.0	0.005	0.10	...	0.6–1.4	…	0.30
ZE10A	…	...	…	...	0.12-0.22	…	…	…	...	1.0-1.5	…	0.30

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Table 9 continues on next page.

Table 9 – *Wrought magnesium alloy specifications (source: Magnesium Elektron [8])*

ELEKTRON Alloy Designation product form and condition	BRITISH		AMERICAN				GERMAN		FRENCH			EUROPEAN
	B.S. Series											
	Aircraft	General Engineering	ASTM Alloy Designation & Temper	ASTM	Federal	AMS	Aircraft Number	DIN 9715 Number	Commercial Designation	Air 9052	AFNOR	AECMA
WE54 Extruded bars & sections	-	-	WE54A-T6	-	-	-	-	-	-	-	-	-
Forgings	-	-	WE54A-T6	-	-	-	-	-	-	-	-	-
WE43 Extruded bars & sections	-	-	WE43B-T6	-	-	-	-	-	-	-	-	-
Forgings Plate Precipitation treated	-	-	WE43B-T6 WE43C-T5	B107	-	- 4485	-	-	-	-	-	-
ZW3 Extruded bars & sections & forgings stock	2 L.505 & L.514	3373 MAG-E-151M	-	-	-	-	-	-	-	-	-	MG-P-43
Forgings	L.514	3372 MAG-E-151M	-	-	-	-	-	-	-	-	-	MG-P-43
AZM Extruded bars & sections & forging stock	L.512 & L.513	3373 MAG-E-121M	AZ61A-F	B107	QQ-M-31B	4350	W.3510	3.5612	M1	G-A6Z1	G-A6Z1	MG-P-63
Extruded tube	2L.503	3373 MAG-E-121M	AZ61A-F	B107	WW-T-825B	-	W.3510	3.5612	M1	G-A6Z1	G-A6Z1	MG-P-63
Forgings	L.513	3372 MAG-E-121M	AZ61A-F	B91	QQ-M-40B	-	-	3.5612	M1	G-A6Z1	G-A6Z1	MG-P-63
AZ80 Extruded bars & sections Precipitation treated	-	-	AZ80A-T5	B107	QQ-M-31B	-	-	-	-	-	-	-
As-extruded	-	-	AZ80A-F	B91	QQ-M31B	-	-	-	-	-	-	-
Forgings Precipitation treated	-	-	AZ80A-T5	B91	QQ-M-40B	4360	W.3515	3.5812	-	G-A7Z1	-	MG-P-61
As-Forged	-	-	AZ80A-F	B91	QQ-M-40B	-	-	-	-	-	-	-

ELEKTRON Alloy Designation product form and condition	BRITISH		AMERICAN				GERMAN		FRENCH			EUROPEAN
	B.S. Series		ASTM Alloy Designation & Temper	ASTM	Federal	AMS	Aircraft Number	DIN 9715 Number	Commercial Designation	Air 9052	AFNOR	AECMA
	Aircraft	General Engineering										
AZ31 Sheet - soft	-	3370 MAG-S-1110	AZ31B-O	B90	QQ-M-44B	4375	W.3504	3.5312	F3	G-A3Z1	G-A3Z1	MG-P-62
Sheet - half hard	-	-	AZ31B-H24	B90	QQ-M-44B	4377	-	-	-	-	-	-
Plate - soft	-	-	AZ31B-O	B90	QQ-M-44B	4375	-	-	-	-	-	-
Plate - half hard	-	-	AZ31B-H24	B90	QQ-M-44B	4377	-	-	-	-	-	-
Plate - three quarters hard	-	-	AZ31B-H26	B90	QQ-M-44B	4376	-	-	-	-	-	-
Plate - extra flat	-	-	AZ31B-O	-	-	4382	-	-	-	-	-	-
Extruded bars & sections	-	3373 MAG-E-111M	AZ31B-F	B107	QQ-M-31B	-	-	3.5312	F3	G-A3Z1	G-A3Z1	MG-P-62
ZM21 Sheet - soft	-	3370 MAG-S-1310	-	-	-	-	-	-	-	-	-	-
- half hard	-	3370 MAG-S-131M	-	-	-	-	-	-	-	-	-	-
Plate	-	3370 MAG-S-131M	-	-	-	-	-	-	-	-	-	-
Extruded bars, sections & tubes	-	3373 MAG-E-131M	-	-	-	-	-	-	-	-	-	-
Forgings	-	3372 MAG-F-131M	-	-	-	-	-	-	-	-	-	-
ZK60 Extruded bars & sections Precipitation treated	-	-	ZK60A-T5	B107	QQ-M-31B	4352	-	-	-	-	-	-
As-extruded	-	-	ZK60A-F	B107	QQ-M-31B	-	-	-	-	-	-	-
Forgings Precipitation treated	-	-	ZK60A-T5	B91	QQ-M-40B	4362	-	-	-	-	-	-
As-forged	-	-	ZK60A-F	B91	QQ-M-40B	-	-	-	-	-	-	-

Continued: Table 9 – Wrought magnesium alloy specifications (source: Magnesium Elektron [8])

4. **Physical and Chemical Properties**

4.1 General Properties

Table 10 compares the physical and chemical properties of die cast magnesium alloys with typical competing materials, i.e., die cast aluminum alloys (A380 and A383), zinc alloys (AG40A and ZA27), and Nylon 6/6 glass fiber reinforced polymer (30%). Magnesium alloys are the lightest metal - only slightly heavier than plastic (nylon) – but significantly higher thermal conductivity and liquidus temperatures (heat resistance) than plastic materials. Compared with aluminum, magnesium alloys have similar thermal expansion coefficient, specific heat, latent heat, casting temperature range and general corrosion rate, but slightly lower thermal and electrical conductivity.

Table 11 lists the physical and chemical properties of wrought magnesium alloys provided by Magnesium Elektron

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Tables 10 & 11 continue on next pages.

Table 10 – Physical properties of die cast magnesium alloys compared with other materials (source: Meridian Lightweight Technologies and US Magnesium)

Physical Properties	Magnesium										Aluminum		Zinc		Plastic
	AZ91D	AM50A	AM60B	AM20	AE42	AE44	MRI 153M	MRI 230D	AS21	AJ62	A380	A383	AG40A	ZA27	Nylon 6/6 GRP (30%)
Density (g/cm^3)	1.81	1.77	1.80	1.75	1.79	1.82	1.80	1.80	1.76	1.80	2.74	2.74	6.60	5.00	1.34
Melting Range F	815-1,108	815-1,238	815-1,139	815-1,180	1,094-1,157	1,071-1,148	946-1,116	977-1,123	815-1,170	959-1,134	1,004-1,103	1,035-1,105	718-732	707-903	
C	435-598	435-620	435-615	435-638	590-625	577-620	508-602	525-606	435-632	515-612	540-595	557-596	381-389	375-484	
Specific Heat (kJ/kg K)	1.020	1.020	1.020	1.020	1.020	1.020	1.090	1.040	1.020	1.150	0.963	0.963	0.418	0.522	
Coefficient of Thermal Expansion (um/m-K)	26.0	26.0	26.0	26.0	26.1	25.2	25.9	25.1	26.1	27.3	22.0	22.0	27.4	26.0	
Thermal Conductivity (W/m-K)	51	65	61	94	84	85	64	77	84	77	96	96	113	123	12
Electrical Conductivity MS/m	6.60	9.10	nm	13.10	11.70	11.70	nm	nm	10.80	nm	nm	nm	nm	nm	
Corrosion Rate mg/cm^2/day	0.05	0.10	0.09	0.60	0.06	0.05	0.09	0.10	0.20	0.04	0.34	0.33	nm	nm	

Sources: Hydro Magnesium September 2005, ASM Handbook; Magnesium Alloys, Dead Sea Magnesium, Noranda Magnesium Data
The mechanical properties of a die cast alloy depend strongly on the fabrication variables involved, as well as on the alloy composition. *Hydro Magnesium nm: not measured

Table 11 – Physical properties of wrought magnesium alloys (source: Magnesium Elektron [8])

Alloy	Specific gravity (20⁰C)	Coefficient of thermal expansion 10^{-6} K^{-1} (20-200⁰C)	Thermal conductivity Wm^{-1} K^{-1} (20⁰C)	Electrical resistivity nΩm (20⁰C)	Specific heat Jkg^{-1} K^{-1} (20-100⁰C)
WE54	1.85	24.6	52	173	960
WE43C	1.82	25.6	58	148	993
ZC71	1.87	26	123	54	960
ZK30	1.8	27.1	125	70	960
AZ61	1.8	27.3	79	143	1000
AZ80	1.8	26	78	145	1050
AZ31	1.77	26	76	100	1040
ZM21	1.78	26	125	70	1040
ZK60	1.83	27.1	121	57	990

4.2 Electromagnetic Interference (EMI) Shielding[1]

One of the most critical physical property requirements of an enclosure for electronic devices is the ability to act as a shield against electromagnetic interferences (EMI). EMI is essentially the impairment of the performance of an electronic system or subsystem by an unwanted electromagnetic disturbance; RFI (radio frequency interference) is a type of EMI which extends over a relatively small portion of the overall frequency band. Any circuit or device that carries an electrical current is a potential source of EMI. The objective in electronic system design is to achieve electromagnetic compatibility between the subsystems in an electronic assembly and between that assembly and other electronic devices that it will encounter in its operating environment.

Any barrier placed between an emitter and a susceptor that diminishes or attenuates the strength of the potential interference qualifies as an EMI shield. The shielding effectiveness of an enclosure is a function of both materials and design, as well as the service conditions. Thus, radiation incident upon a shielding barrier is either absorbed, reflected or transmitted. For metal shields and high impedance fields, most of the energy is reflected; if the magnetic field is dominant, absorption is the principal mode of attenuation.

4.2.1 EMI: Metals vs. Plastics

Most metals are inherently conductive and therefore reflect and absorb EMI to an appreciable degree. The amount of EMI shielding provided by a metal enclosure depends upon the nature and frequency of the radiation, the absorbent and reflective components of the radiation, the conductivity and magnetic permeability of the metal, as well as the distance of the enclosure from the radiation source. Since plastics are inherently insulative and thus transparent to electromagnetic radiation, plastic enclosures must rely on surface modification or incorporation of metal particles to satisfy shielding requirements. Both of these approaches carry significant cost penalties, with the latter also leading to decreased tool (die) life.

The current competition between plastics and metals for EMI shielding is dependent on both the inherent advantages and disadvantages of these materials in such applications and on the evolving aesthetic/electronic/mechanical requirements of the enclosures. For metals as a group, the relevant advantages are:

- Inherent conductivity and therefore inherent EMI shielding capability
- Low raw material costs

[1] This section is based on a Hydro Magnesium Technical data sheet.

- Structural strength in thin-wall designs
- Durability in service

As the design of electronic units moves toward more power in less space, the ease of fabrication and the heat resistance of metals also become more significant factors.

4.2.2 Advantages of Magnesium for Die Cast Shielding Enclosures

The advantages are summarized as follows:

- Very low density, leading to lightweight, portable units
- Low heat capacity, a significant factor in achieving high production rates.
- Very low solubility for iron, providing a major basis for superior tooling life.
- Excellent fluidity, an important contributor to castings with thin walls, minimum draft and dimensional accuracy.
- For shielding applications dependent upon reflection, the weight saving benefit of magnesium enclosures extends over the full frequency spectrum.
- For shielding by absorption, die cast enclosures of magnesium and aluminum provide nominally equivalent shielding effectiveness on an equal weight basis (the higher conductivity of the aluminum is offset by the lower density of the magnesium). As frequency increases, however, the wall thickness required for a given level of shielding effectiveness becomes progressively smaller. Above approximately 1 MHz, the required thickness of the enclosure becomes defined by castability (fluidity) limits and structural integrity requirements. In this portion of the frequency spectrum, which encompasses most commercial applications, the thinner wall casting capability and lower density of magnesium provide significant advantages in weight and cost reduction over die cast aluminum.

In summary, magnesium enclosures for EMI shielding provide significant advantages over both plastic and alternative metal housings.

5. Mechanical Properties

5.1 Mechanical Properties at Room Temperature

5.1.1 Gravity Cast Alloys

Table 12 summarizes the room-temperature mechanical properties of gravity cast magnesium alloys. These alloys can be divided into two groups, i.e., alloys with and without zirconium additions.

Mg-Al based alloys: As shown in Table 12, Mg-Al based alloys including AZ91 offer limited mechanical properties and suffer from micro porosity in sand and gravity permanent mold castings. These alloys containing 6-10% Al are heat-treatable due to the precipitation of ß phase ($Mg_{17}Al_{12}$) in the microstructure. Grain refinement is generally needed to obtain improved mechanical properties in these alloys.

Zirconium-containing alloys: Zirconium is the most effective grain-refiner in Al-free magnesium alloys. Due to the effective grain refinement provided by Zr and precipitation hardening provided by alloying with Zn, RE, Ag and Y, these Zr-containing alloys generally have higher mechanical properties than Mg-Al based alloys.

Table 12 – Typical room-temperature mechanical properties of gravity cast magnesium alloys

Alloy	Nominal Composition						Tensile Properties		
	Al	Mn	RE	Zn	Zr	Other	UTS, MPa	0.2% YS, MPa	El%
AM100A-T61	10.0	0.10					275	150	1
AZ63A-T6	6.0	0.15		3.0			275	130	5
AZ81A-T4	7.6	0.13		0.7			275	83	15
AZ91C, E-T6	8.7	0.13		0.7			275	145	6
AZ92A-T6	9.0	0.10		3.0			275	150	3
EQ21A-T6					0.7	1.5 Ag, 3.1 Di, 0.05-0.10 Cu	235	195	2
EV31A – T6			4.6	0.3	0.5		280	170	5
EZ33A-T5			3,3	3.7	0.6		160	110	2
K1A-F*					0.7		180	55	19
QE22A-T6					0.7	3.5 Ag, 3.1 Di	260	195	3
WE43A-T6			3.4		0.7	4.0 Y	250	185	2
WE54A-T6			3.0		0.7	5.2 Y	250	205	2
ZC63A-T6		0.25		6.0		3.7 Cu	210		4
ZE41A-T5			1.2	4.2	0.7		205	140	3.5
ZE63A-T6			3.6	5.8	0.7		300	195	10
ZK51A-T5**				4.6	0.7		205	165	3.5
ZK61A-T5**				6.0	0.7		310	185	
ZK61A-T6**				6.0	0.7		310	195	10

* good damping capacity but poor mechanical properties
** poor foundry characteristics; never used in permanent molds

Note: Alloys with thorium are removed from this list as the thorium has been classified as a hazardous material.

5.1.2 Die Cast Alloys

Table 13 provides the properties of die cast magnesium alloys compared with aluminum and zinc alloys, which includes some of the new creep-resistant alloys such as MRI153M and MRI230D and AJ62. The workhorse die cast AZ91 alloy provides similar yield strength and ductility of A380 aluminum alloy; providing essentially the same functionality with significant mass savings compared to aluminum or zinc alloys. On the other hand, AM60 and AM50 offer unique advantages due to their higher ductility (10% elongation) and higher impact strength compared to die cast A380 alloy.

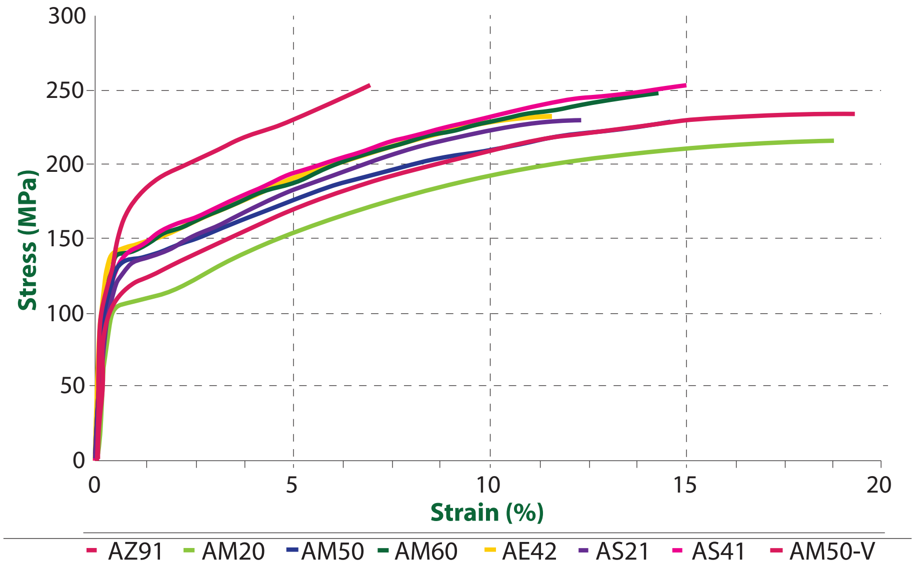


Figure 1 – Typical stress-strain curves for die cast alloys.

Table 13 – Typical mechanical properties of die magnesium alloys compared with aluminum and zinc alloys (source: Meridian Lightweight Technologies [9])

Mechanical Properties	Magnesium										Aluminum		Zinc	
	AZ91D	AM50A	AM60B	AM20	AE42	AE44	MRI 153M	MRI 230D	AS21	AJ62	A380	A383	AG40A	ZA27
Ultimate Tensile Strength (MPa)	240	210	225	190	230	245	250	245	175	234	320	310	283	426
Yield Strength (MPa)	160	125	130	90	145	142	170	180	110	140	160	150		365
Elongation (%) 2 in (51mm)	3	10	8	12	10	10	6	5	9	7	3.5	3.5	10	2
Hardness Brinell	70	60	65	45	60	62	72	71	55	61	80	75	82	115
Elastic Modulus (GPa)	45	45	45	45	45	45	45	45	45	45	71	71		78
Charpy Impact (unnotched) (J)	6	18	17	18	5	15	8	6	5	13	4	4	53	4

Sources: Hydro Magnesium September 2005, ASM Handbook; Magnesium Alloys, Dead Sea Magnesium, Noranda Magnesium Data
The mechanical properties of a die cast alloy depend strongly on the fabrication variables involved, as well as on the alloy composition.

*Hydro Magnesium nm: not measured

5.1.3 Wrought Alloys

For wrought magnesium alloys, the mechanical properties are highly dependent on the product form (forging, extrusion or sheet), shape/size (bar, tube and thickness) and heat treatment conditions of the final products. Table 14 shows typical properties of wrought magnesium alloy products from Magnesium Electron[8] and Table 15 lists typical room temperature mechanical properties of magnesium sheet alloys form POSCO in Korea [13].

Table 14 – Typical room-temperature mechanical properties of wrought magnesium alloys compared to other materials (source: Magnesium Elektron [8])

Typical Chemical Composition - Major Alloying Elements %	ELEKTRON Alloy	Tensile Properties[B]			Compressive Properties		Fatigue Properties[B]		Hardness	Description
		0.2% Proof Stress (MPa)	Tensile Strength (MPa)	Elongation[C] (%)	0.2% Proof Stress (MPa)	Compressive Strength (MPa)	Unnotched (MPa)	Notched (MPa)	v.p.n.	
Y 5.25 Nd 3.5[A] Zr 0.5	WE54 Extruded bars & sections Precipitation treated	(180)	(280)	(6)	-	-	-	-	75-95	High strength at elevated temperatures particularly in the fully heat treated condition.
	Fully heat treated	(160)	(250)	(6)	-	-	-	-	75-95	
	Forgings[E] Precipitation treated	(165)	(310)	(4)	-	-	-	-	-	
	Fully heat treated	(170)	(260)	(6)	-	-	-	-	-	
Y 4.0 Nd 3.0[A] Zr 0.5	WE43C Extruded bars Precipitation treated	(195)	(303)	(6)	-	252	195	-	75-95	High strength aerospace alloy at elevated temperatures particularly in the fully heat treated condition.
	WE43B Forgings[E] Precipitation treated	(155)	(285)	(6)	-	-	-	-	-	
	Fully heat treated	(165)	(265)	(6)	-	-	-	-	-	
Zn 3.0 Zr 0.6	ZW3 Extruded bars & sections	200	280	8	-	-	-	-	65-75	High Strength extrusion and forging alloy. Weldable under good conditions.
	0-10mm 10-100mm	225	305	8	200-250	385-465	110-135	85-95	65-75	
	Extruded forging stock	195	280	8	-	-	-	-	65-75	
	0-10mm 10-100mm	205	290	8			-	-	65-75	
	Forgings[E]	205	290	7	165-215	370-440	-	-	60-80	
Al 6.0 Zn 1.0 Mn 0.3	AZM Extruded bars & sections & extruded forging stock	180	270	8	130-180	370-420	125-135	90-95	60-70	General purpose alloy. Gas and arc weldable.
	0-75mm 75-150mm	160	250	7	115-165	340-400	-	-	55-65	
	Extruded tube	150	260	7	130-180		-	-	60-70	
	Forgings[E]	160	275	7	130-165	340-400	115-125	80-90	60-70	

Al 8.5 Zn 0.5 Mn 0.2min	AZ80 Extrusions Precipitation treated 0-6.3mm	205	325	4	-	-	-	-		High strength alloy for extrusions and forgings of simple design.
	6.3=60mm	230	330	3	-	-	-	-		
	60-130mm	205	310	1	-	-	-	-		
	Forgings[E] Precipitation treated	200	290	6	-	-	-	-	60	
Al 3.0 Zn 1.0 Mn 0.3	AZ31 Sheet - soft	105-125	220	11	85	-	-	-	50-65	Medium strength sheet and extrusion alloy. Good formability Weldable.
	- stabilized half hard	200	270	5	165	-	-	-		
	Plate - stabilized half hard 6-25m	150-180	250-260	7	165	-	-	-	-	
	25-75mm	125-135				-	-	-	-	
	Extruded bars & sections & tubes	125-135	235	7	60-70	-	-	-	-	
	0-10mm	150	230	8	-	-	-	-	50-65	
	10-75mm	160	245	10	-	-	-	-	50-60	
Al 3.0 Zn 1.0	Tooling Plate 6-150mm	(100)	(200)	(8)	-	-	-	-	-	
Zn 2.0 Mn 1.0	ZM21 Sheet - soft	(120)	200-265	10-12	-	-	-	-	-	Medium strength sheet and extrusion alloy. Easily formed. Fully weldable by argon arc process.
	- half hard	165	250	5-8	-	-	-	-	-	
	Plate 6-25mm	(120)	220	8-10	-	-	-	-	-	
	Extruded bars, sections & tubes 10mm	150	230	8	-	-	-	-	50-65	
	10-75mm	160	245	10	-	-	-	-	50-60	
	Forgings[E]	125	200	9	-	-	-	-		
Zn 6.0 Zr 0.6	ZK60 Die Forgings[E] Precipitation treated	180	290	6	-	-	-	-	-	High strength alloy for forgings and extrusions.
	Extruded bars & sections up to 1300mm^2	250	310	3	205	-	-	-	-	
	over 1300 to 1900mm^2	250	310	3	195	-	-	-	-	
	over 1900 to 3200mm^2	250	310	3	170	-	-	-	-	
	over 3200 to 6400mm^2	235	310	5	160	-	-	-	-	
	over 6400 to 16100mm^2	235	310	5	150	-	-	-	-	
	over 16100 to 25800mm^2	215	295	5	140	-	-	-	-	

Approximate conversion factors 1 Mpa=0.065 T.S.I.=0.145 K.S.I.
Larger sizes than those shown above are available: when required, property levels will be by agreement.

[A] Includes primary neodymium with other heavy rare earths

[B] The tensile properties quoted are the specification minima for the first specification listed for that alloy and condition. Where a range is quoted the specification requirements depend on product thickness. Bracketed values are for information only.

[C] Elongation value are based on a gauge length of $5.65\sqrt{A}$, except in case of thin material where a gauge length of 50mm may be used (see B.S. 2 L.500,3370 and 3373). With the latter gauge length, elongation requirements for sheet and plate depend on thickness and a range of minima is quoted.

[D] Endurance values for 50×10^6 reversals in rotating bending-type tests; semi circular notch, radius 1.2mm; S.C.F. approx. 2.

[E] Forging properties quoted are those in the most favourable direction of flow; the manufacturer should be consulted on directionality.

Table 15 – Typical room-temperature mechanical properties of magnesium sheet alloys from POSCO (source: POSCO [13])

Alloy	Thick.(mm)	Y.P(MPa)	T.S (MPa)	Elongation (%)	Ericsen Value (mm)
AZ31	0.4~0.8	190~210	260~280	19	2.5~3.0
	1.0~2.0	170~190	250~270	17	
	2.5~3.0	155~170	240~260	14	
E-form	0.4~0.5	140~180	240~265	15~25	~9.0
	1.0~1.4	140~160	245~260	20~25	

*AZ31B vs E-form
-AZ31B: Most widely used Mg alloy for rolled sheet. Good elongation, appl for auto parts, etc.
-E-form Mg: Better formability than AZ31B at low temperature (for automotive parts, etc.)
E-form is the name of POSCO's new proprietary Mg alloy, which means Easy and Economic Formable

5.2 Mechanical Properties at Elevated Temperatures

5.2.1 Die Cast Alloys

Table 16 complies the tensile properties of die cast magnesium alloys at various temperatures up to 150°C. It is evident that conventional AM and AZ alloys lose their yield strength at temperatures above 100°C. AE42 can retain reasonable mechanical properties up to 120°C, but is not recommended for applications at temperatures above that (see significant drop in strength at 150°C). Figure 2 shows the tensile and fatigue properties of a new creep-resistant alloy AE44 at elevated temperatures.

Table 17 shows the 100-hour total creep strain values of die cast magnesium alloys at various temperatures and stress levels. It is evident that creep strain increases at higher temperature/stress levels. While AS alloys have slightly better creep resistance than AZ and AM alloys, AE42 has the best creep resistance in all test conditions. It is also evident that the 150°C creep strain of all alloys is significantly higher than that at 100°C. Table 18 and Figure 3 show improved elevated temperature tensile and creep properties of new magnesium alloys. Figure 4 compares the creep resistance of several magnesium alloys at 150°C and 90 MPa.

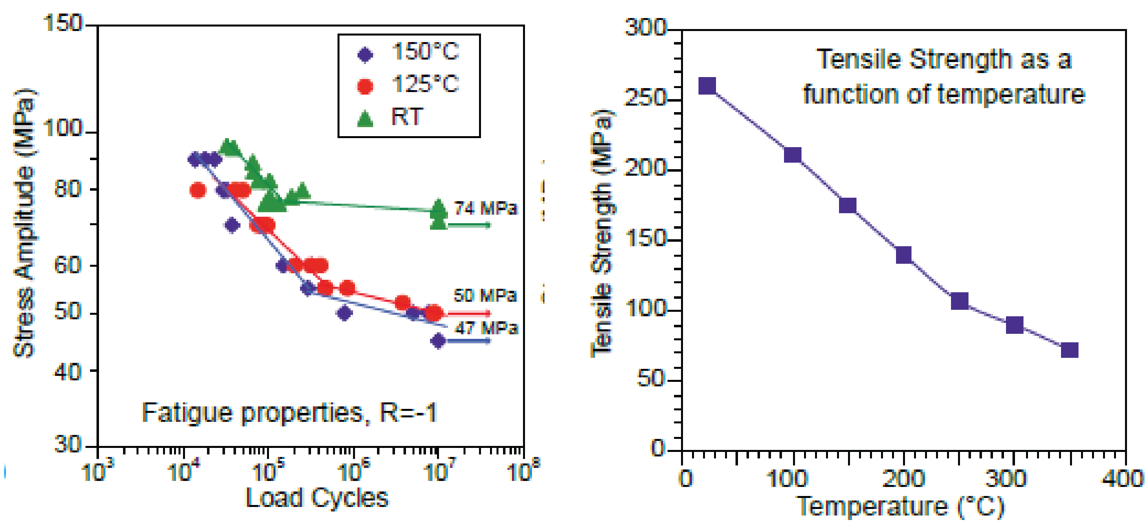


Figure 2 – Tensile and fatigue properties of creep-resistant alloy AE44 at elevated temperatures (Source: Magontec).

Table 16 – Tensile properties of die cast magnesium alloys at various temperatures

AM20 die cast alloy	**Mean Values (standard deviation)**		
Test temperature, °C	**UTS (MPa)**	**TYS (MPa)**	**Elongation (%)**
23	217 (3)	99 (7)	18.8 (2.0)
75	191 (2)	95 (8)	27.1 (1.9)
100	176 (2)	88 (4)	24.6 (1.0)
125	155 (7)	81 (5)	20.0 (2.9)
150	135 (6)	77 (3)	22.0 (6.1)

AM60 die cast alloy	**Mean Values (standard deviation)**		
Test temperature, °C	**UTS (MPa)**	**TYS (MPa)**	**Elongation (%)**
23	250 (12)	131 (6)	14.3 (2.9)
75	223 (9)	128 (4)	14.0 (1.8)
100	216 (2)	115 (2)	24.9 (1.8)
150	152 (3)	100 (6)	24.0 (9.2)

AS41 die cast alloy	**Mean Values (standard deviation)**		
Test temperature, °C	**UTS (MPa)**	**TYS (MPa)**	**Elongation (%)**
23	253 (4)	140 (4)	15.3 (2.0)
75	203 (3)	108 (5)	21.3 (3.0)
100	153 (4)	94 (3)	23.7 (3.9)
150	108 (2)	79 (3)	27.0 (2.2)

AE42 die cast alloy	**Mean Values (standard deviation)**		
Test temperature, °C	**UTS (MPa)**	**TYS (MPa)**	**Elongation (%)**
20	247 (31)	134 (4)	7.9 (2.6)
40	248 (11)	137 (3)	9.0 (1.5)
50	227 (13)	125 (11)	10.2 (2.7)
60	232 (10)	132 (5)	11.4 (3.3)
80	221 (1)	128 (3)	14.8 (2.2)
100	206 (4)	118 (2)	16.9 (1.5)
120	185 (4)	111 (1)	18.2 (1.5)
150	157 (1)	97 (4)	23.4 (5.6)

Table 17 – Total creep strain (standard deviation values in brackets) of die cast magnesium alloys after 100 hours' test at various temperatures and stresses

Alloy	100°C		150°C		200°C
	50 MPa	100 MPa	30 MPa	50 MPa	30 MPa
AZ91	0.07 (0.02)	0.55 (0.11)	0.25 (0.14)	1.20 (0.20)	0.55 (0.09)
AS41				0.33 (0.05)	0.29 (0.03)
AS21		0.29 (0.03)	0.29 (0.03)	0.29 (0.03)	0.29 (0.03)
AE42	0.05 (0.02)	0.28 (0.05)	0.09 (0.03)	0.15 (0.03)	
AM60	0.07 (0.02)	0.97 (0.12)	0.45 (0.04)	1.25 (0.06)	
AM20	0.04 (0.01)		0.16 (0.03)	0.35 (0.04)	

Table 18 - Typical mechanical properties of MRI alloys compared to A380 aluminium alloy (source: Dead Sea Magnesium)

Properties	MRI 230D	MRI 153M	A380
TYS (MPa) 20 °C 150 °C 175 °C	 180 150 145	 170 135 125	 165 150 135
UTS (MPa) 20 °C 150 °C 175 °C	 245 205 178	 250 190 172	 330 235 195
Elongation (%) 20 °C 150 °C 175 °C	 5 16 18	 6 17 22	 3 5 6
CYS (MPa) 20 °C 150 °C 175 °C	 175 145 140	 165 130 120	-

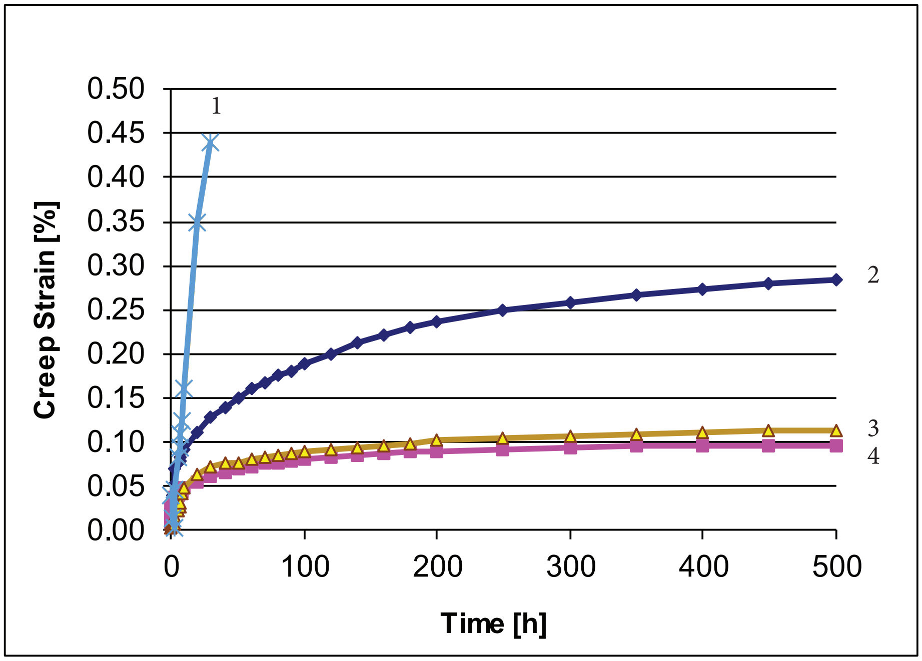


Fig. 3a - Comparative creep behavior of MRI alloys at 135°C under a stress of 85 MPa 1-AZ91D, 2- MRI153M, 3-A380, 4 MRI230D (source: Dead Sea Magnesium)

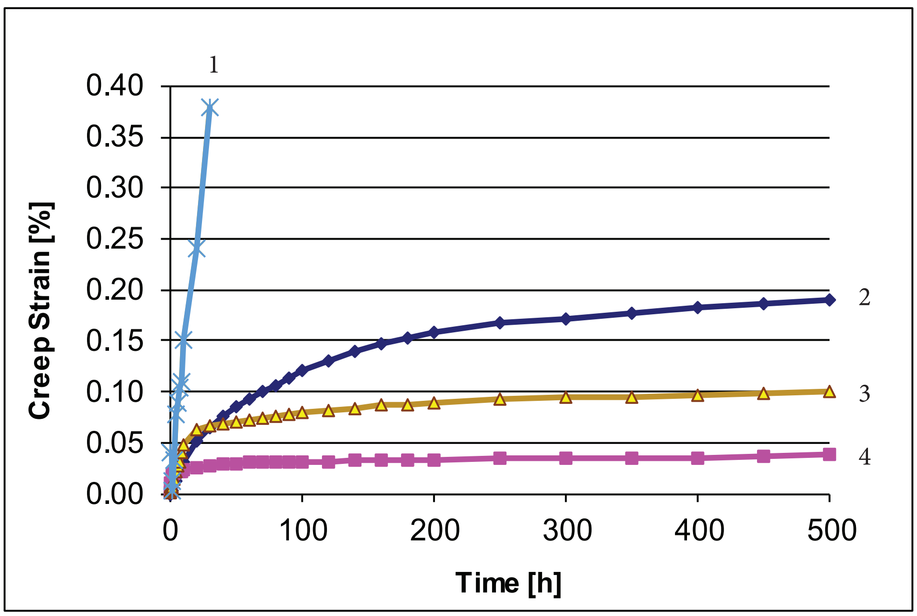


Fig. 3b - Comparative creep behavior of MRI alloys at 150°C under a stress of 50 MPa 1-AZ91D, 2- MRI153M, 3-A380, 4 MRI230D (source: Dead Sea Magnesium)

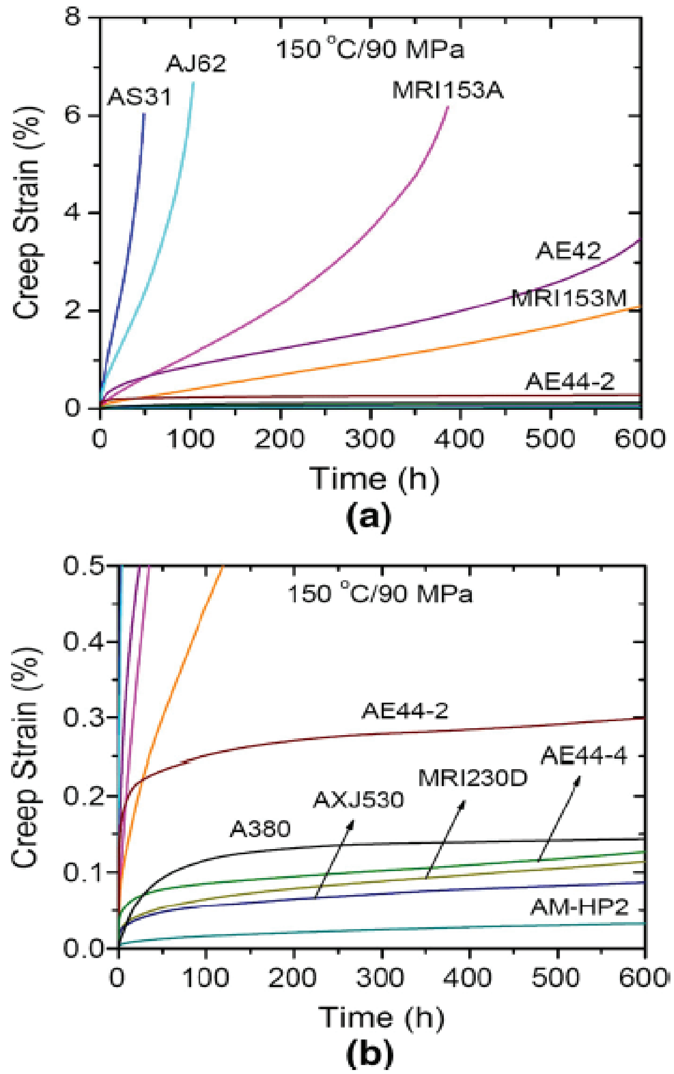


Fig. 4 - Creep resistance of different alloys at 150°C under a stress of 90 MPa: (b) shows an enlarged portion of (a) (source: Magontec)

5.2.2 Wrought alloys

Figures 5 and 6 show tensile properties vs. temperature of AZ31-H24 sheet/plate and ZK60A forgings, respectively. Similar to cast magnesium alloys, the tensile properties of wrought alloys drop significantly with temperature.

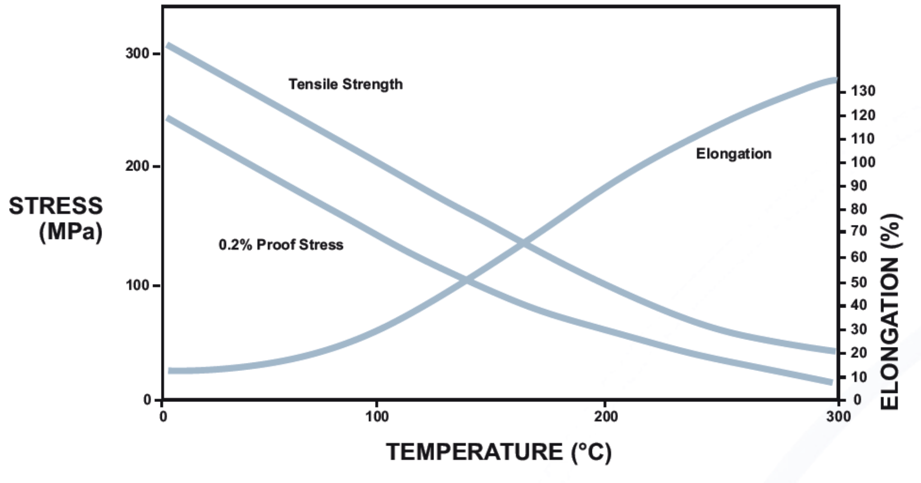


Figure 5 – Tensile properties vs. temperature of AZ31-H24 sheet/plate (Source: Magnesium Elektron)

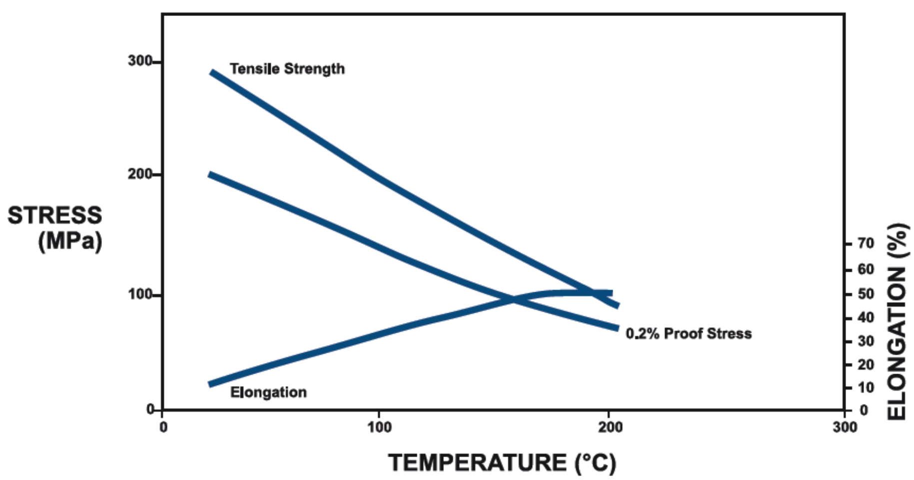
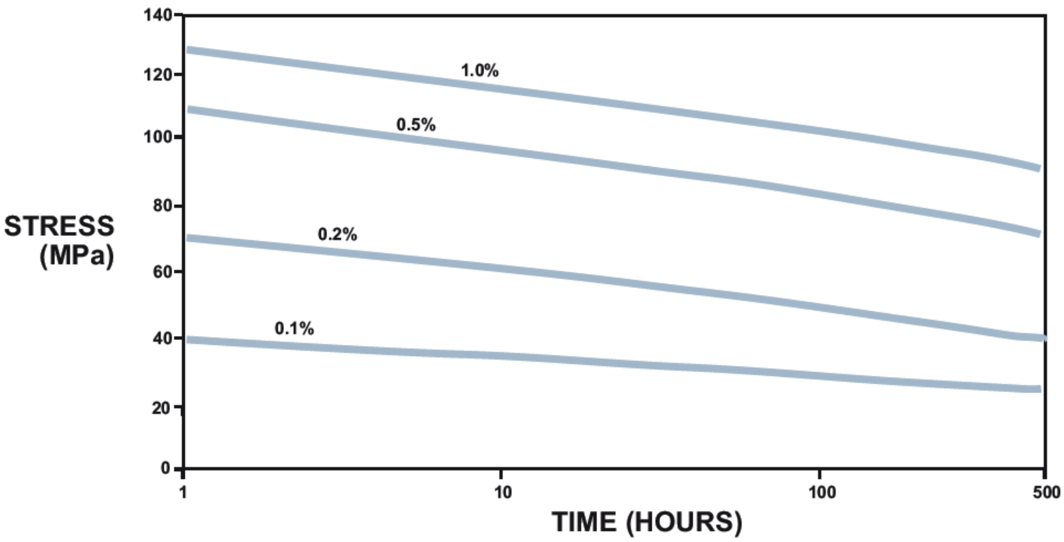
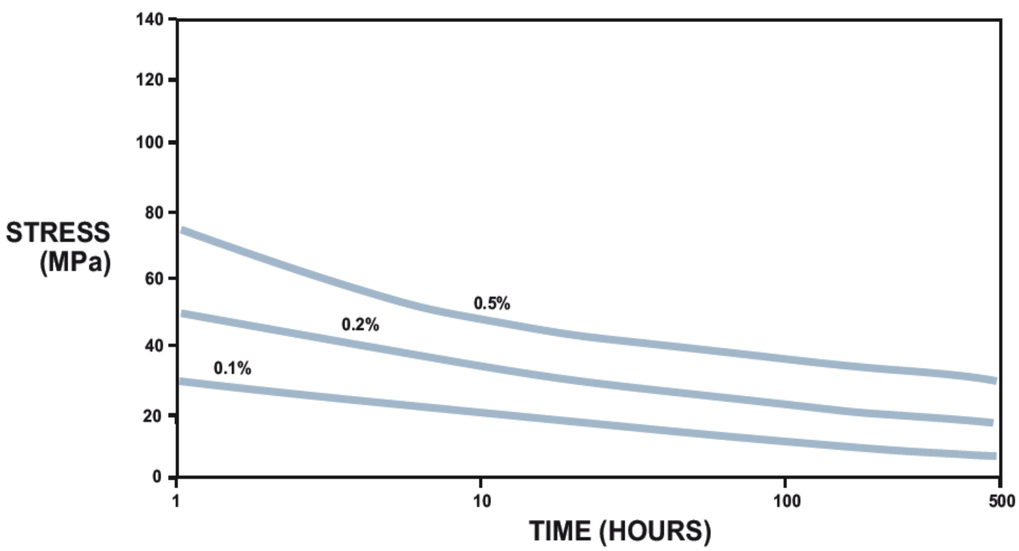


Figure 6 – Tensile properties vs. temperature of ZK60A forgings (Source: Magnesium Elektron)

Figures 7 and 8 show the stress vs. time relationship (stress relaxation) for specified creep of AZ31-H24 sheet/plate and ZK60A forgings, respectively. These results also show that the creep strain of both wrought alloys drops considerably faster with time at 150°C than at 100°C.

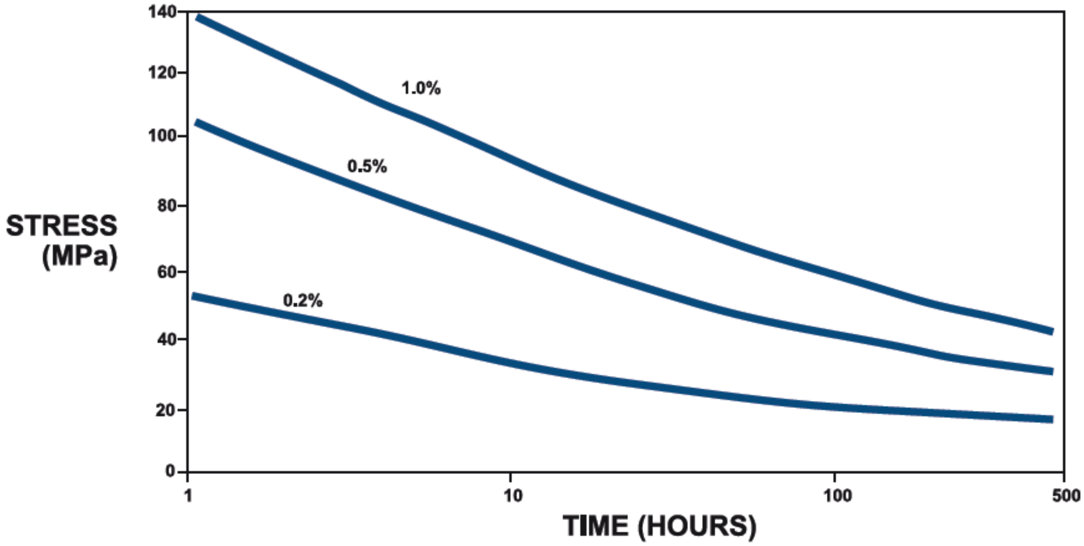


(a) 100°C

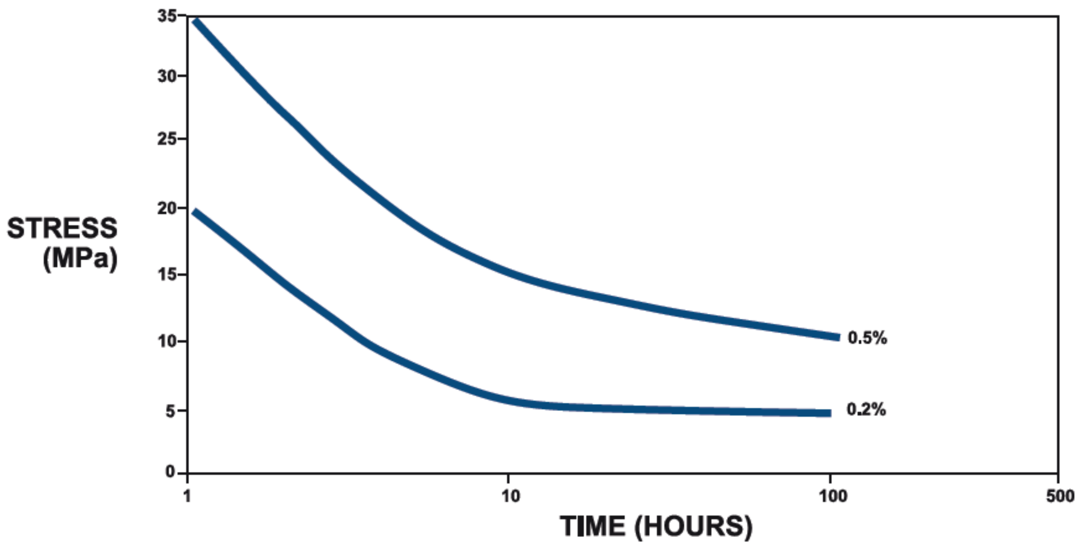


(b) 150°C

Figure 7 – Stress vs. time relationship (stress relaxation) for specified creep of AZ31-H24 sheet: (a) 100°C; and (b) 150°C (Source: Magnesium Elektron).



(a) 100°C



(b) 150°C

Figure 8 – Stress vs. time relationship (stress relaxation) for specified creep of ZK60A-T5 forgings: (a) 100°C; and (b) 150°C (Source: Magnesium Elektron).

6. Design Considerations: Potential Mass Savings [10]

Table 19 summarizes the mechanical and physical properties of typical cast and wrought magnesium alloys in comparison with other materials for structural applications [10-12]. Materials selection for structural applications is an extremely complex process in which component geometries, loading conditions, material properties, manufacturing processes and costs are all playing important roles [6, 11, 14]. As the bending mode is often the primary loading condition in many structures, the following analyses on structural performance and mass saving potential of magnesium over mild steel are based on the bending stiffness and strength calculations.

For a **panel** (plate) under bending loads, the minimum thickness *(t)* and mass *(m)* can be calculated using the "materials performance index" concept [14]. Designating steel and magnesium properties with subscripts *S* and *Mg*, the thickness ratios and mass ratios of components made of the two materials for an equal stiffness design may be expressed as:

$$t_{Mg}/t_S = (E_S/E_{Mg})^{1/3} \qquad (1)$$

$$m_{Mg}/m_S = (d_{Mg}/d_S)(E_S/E_{Mg})^{1/3} \qquad (2)$$

where *E* and *d* are the elastic modulus and density of the materials, respectively. Using the property data as shown in Table 1.2, the thickness and mass ratios of magnesium (AZ91 alloy) vs. a mild steel beam can be calculated:

$$t_{Mg}/t_S = 1.67 \qquad (3)$$

$$m_{Mg}/m_S = 0.39 \qquad (4)$$

Therefore, in order to achieve the same bending stiffness, a magnesium panel will be required to have 1.67 times the thickness of a steel one, with a mass saving of 61%. For bending strength-limited design (same bending strength at minimum mass), such ratios for AZ91 magnesium alloy vs. a mild steel become:

$$t_{Mg}/t_S = (YS_S/YS_{Mg})^{1/2} = 1.06 \qquad (5)$$

$$m_{Mg}/m_S = (d_{Mg}/d_S)(YS_S/YS_{Mg})^{1/2} = 0.25 \qquad (6)$$

where *YS* is the yield strength of the materials.

For a **beam** in an equal stiffness design, Eqs. (1) and (2) became:

$$t_{Mg}/t_S = (E_S/E_{Mg})^{1/2} \qquad (7)$$

$$m_{Mg}/m_S = (d_{Mg}/d_S)(E_S/E_{Mg})^{1/2} \qquad (8)$$

Similarly, for a solid beam in an equal strength design, Eqs. (5) and (6) became:

$$t_{Mg}/t_S = (YS_S/YS_{Mg})^{2/3} \qquad (9)$$

$$m_{Mg}/m_S = (d_{Mg}/d_S)(YS_S/YS_{Mg})^{2/3} \qquad (10)$$

Material	Cast Mg		Wrought Mg		Cast Iron	Steel		Cast Al		Wrought Al		Polymers (PC/ABS)	GFRP[2] (glass/polyester)		CFRP[3] (carbon/epoxy)	
Alloy/Grade	AZ91	AM50	AZ80 -T5	AZ31 -H24	Class 40	Mild steel Grade 4	AHSS[1] DP340/ 600	380	A356-T6	6061-T6	5182-H24/ 6111-T8X[5]	Dow Pulse 2000	Structural (50% uniaxial)	Exterior (27%)	Structural (58% uniaxial)	Exterior (60%)
Process/ Product	die cast	die cast	extrusion	sheet	sand cast	sheet	sheet	die cast	P/M[4] cast	extrusion	sheet	injection molding	liquid molding	compression molding	liquid/ compression molding	autoclave molding
Density (d, g/cm^3)	1.81	1.77	1.80	1.77	7.15	7.80	7.80	2.68	2.76	2.70	2.70	1.13	2.0	1.6	1.5	1.5
Elastic Modulus (E, GPa)	45	45	45	45	100	210	210	71	72	69	70	2.3	48	9	189	56
Yield Strength (YS, MPa)	160	125	275	220	N/A	180	340	159	186	275	235/ 230	53	1240	160	1050	712
Ultimate Tensile Strength (S_t, MPa)	240	210	380	290	293	320	600	324	262	310	310/ 320	55				
Elongation (e_f, %)	3	10	7	15	0	45	23	3	5	12	8/20	5 at yield and 125 at break	< 1	2	< 1	< 1
Fatigue Strength (S_f, MPa)	85	85	180	120	128	125	228	138	90	95	120/ 186		N/A	N/A	N/A	N/A
Thermal Cond. (l, W/m.K)	51	65	78	77	41	46		96	159	167	123		0.6	0.3	0.5	0.5
Thermal Exp. Coeff. (d, µm/m.K)	26	26	26	26	10.5	11.70		22	21.5	23.6	24.1/ 23.4	74	12	14	2	4
Melting Temp. (T_m, °C)	598	620	610	630	1175	1515		595	615	652	638/ 585	143 (softening temp.)	130-160 (molding temp.)		175 (max. service temp.)	

1. AHSS: advanced high strength steel;
2. GFRP: glass fiber reinforced polymer
3. CFRP: carbon fiber reinforced polymer;
4. P/M: permanent mold;
5. T8X: simulated paint-bake (2% strain plus 30 min. at 177°C).

Table 19 - Comparison of mechanical and physical properties of various structural materials [10]

Based on the above nomenclature and the property data in Table 19, Table 20 summarizes the thickness and mass ratios of various materials compared with mild steel, for solid panel and beam designs, respectively. For a generic comparison, the uniaxial properties of structural composites are not included in the analysis. Instead, the "quasi-isotropic" properties of exterior GFRP and CFRP composites are used to compare with the isotropic properties of other materials for mass saving analysis. Figures 9 and 10 highlight the thickness ratios and the resultant percentage mass savings of the materials when replacing a mild steel component. These results show that magnesium alloys have higher mass saving potential when compared to AHSS, aluminum and polymers, in substituting mild steel structures for equal stiffness or strength. To overcome its much lower elastic modulus, a polymer part will have to be reinforced with fibers or a metal-polymer hybrid structure has to be used. Compared to GFRP composites, magnesium alloys have higher mass saving potential for equal stiffness and similar savings for equal strength. While CFRP has the highest mass saving potential, wrought magnesium alloys offer slightly less mass savings at a lower cost.

Table 20 - Thickness and mass ratios of various materials compared to mild steel for equal bending stiffness- and strength-limited design

Material		AHSS	Al (Cast)	Al (Wrought)	Mg (Cast)	Mg (Wrought)	PC/ABS	GFRP (Exterior)	CFRP (Exterior)
Equal Stiffness Panel	Thickness Ratio	1.00	1.44	1.45	1.67	1.67	4.50	2.86	1.55
	Mass Ratio	1.00	0.49	0.50	0.39	0.39	0.65	0.59	0.30
Equal Strength Panel	Thickness Ratio	0.73	1.06	0.81	1.06	0.81	1.84	1.06	0.50
	Mass Ratio	0.73	0.37	0.28	0.25	0.19	0.27	0.22	0.10
Equal Stiffness Beam	Thickness Ratio	1.00	1.72	1.74	2.16	2.16	9.56	4.83	1.94
	Mass Ratio	1.00	0.59	0.60	0.50	0.50	1.38	0.99	0.37
Equal Strength Beam	Thickness Ratio	0.65	1.09	0.75	1.08	0.75	2.26	1.08	0.40
	Mass Ratio	0.65	0.37	0.26	0.25	0.17	0.33	0.22	0.08

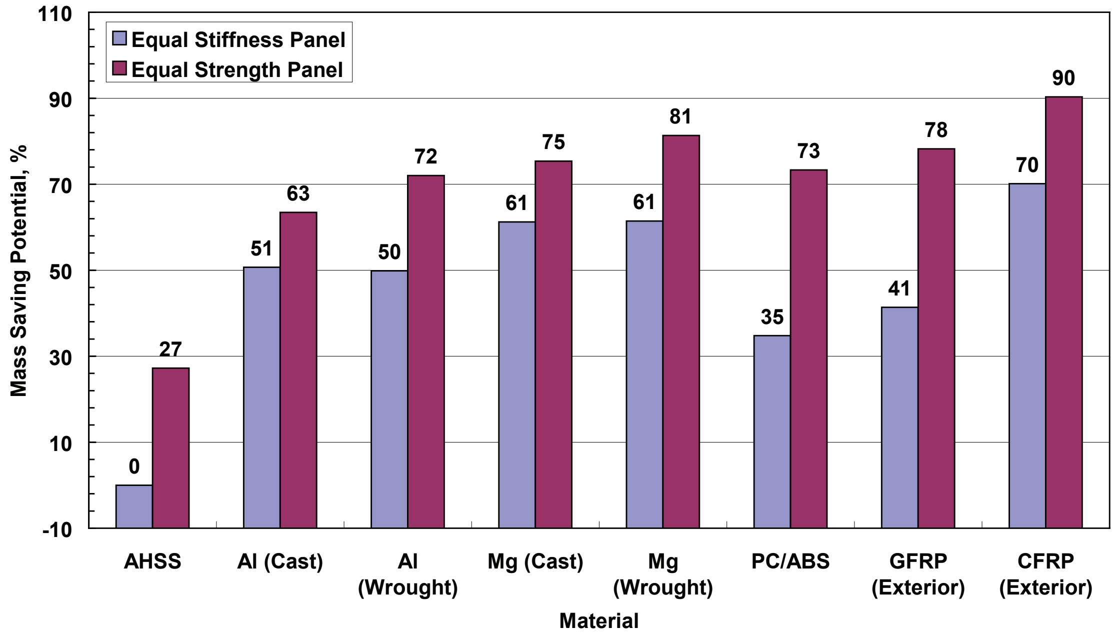


Figure 9 - Percentage mass savings of various materials vs. mild steel for designing a structural panel with equivalent bending stiffness or bending strength.

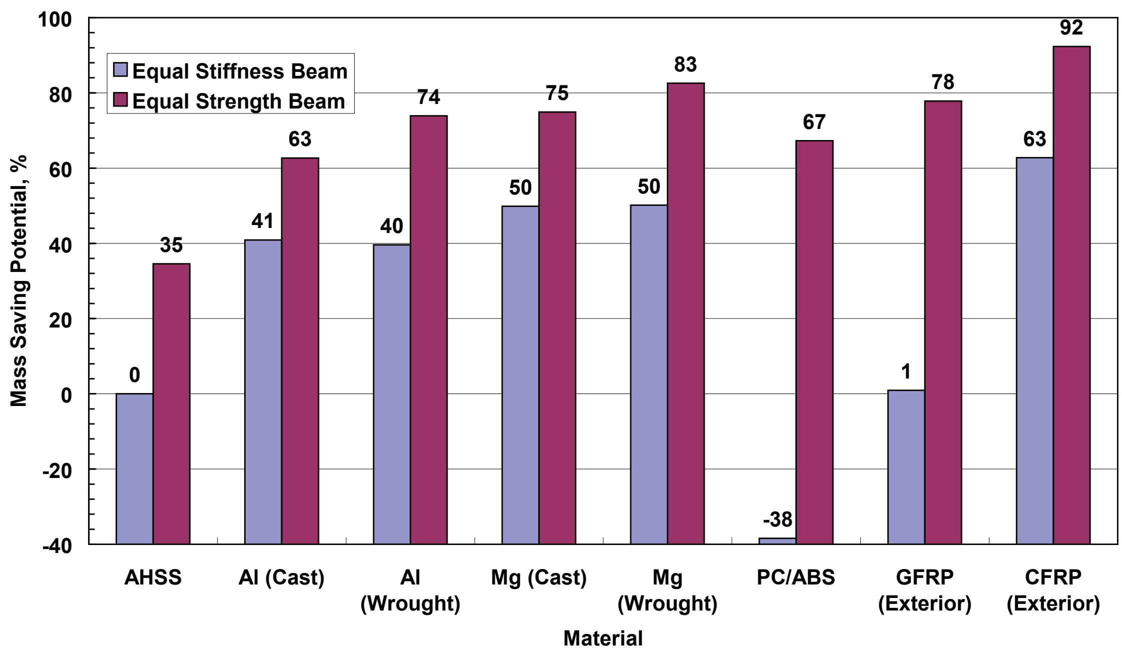


Figure 10 - Percentage mass savings of various materials vs. mild steel for designing a structural beam with equivalent bending stiffness or bending strength.

7. Corrosion and Finishing [11]

7.1 General Corrosion

The corrosion properties of magnesium alloys are partially determined by the composition and content of impurity elements, but the alloy microstructure and the properties of the oxide film are also important factors. As illustrated in Figure 11, the alloying elements form intermetallic particles with the impurity elements, and these intermetallic particles are more noble than the magnesium matrix (α-Mg). In a corrosive environment, corrosion pits are initiated in the α-Mg close to these intermetallics, i.e., there are *galvanic cells* in the metal. The corrosion attack grows in the α-Mg until it hits the grain boundaries. These boundaries contain the β-phase ($Mg_{17}Al_{12}$), which is more corrosion-resistant and more noble than the α-Mg. Due to the better corrosion resistance, the β-phase acts as a barrier for the corrosion growth. The microstructure is therefore important, because with a fine microstructure, there are many barriers present. This is the case for die castings, where rapid cooling gives the fine microstructure. Generally, the finest and most corrosion resistant structure is found near the surface of the casting, and the microstructure coarsens toward the interior of the metal. As shown in Figure 12, the corrosion resistance increases with increasing aluminum content, primarily because of the following:

- Higher aluminum content gives more aluminum in the α-magnesium and thus a more corrosion resistant matrix.
- Higher aluminum content gives more β-phase and thus more corrosion barriers.

By adding silicon or rare earth elements, good corrosion-resistant alloys can be made in the composition range of 2 - 4% aluminum. As shown in Figures 12 and 13, AE42 exhibits a corrosion rate in salt spray comparable to AZ91D, while AS21B is comparable to AM50A and AM60B. Figure 11 also shows that the general corrosion resistance of die cast magnesium alloys is better than that of aluminum alloy A380.

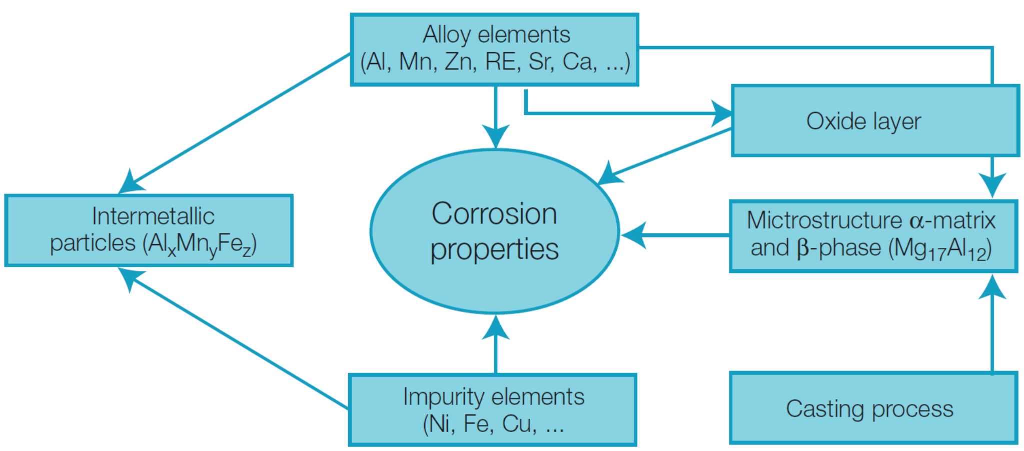
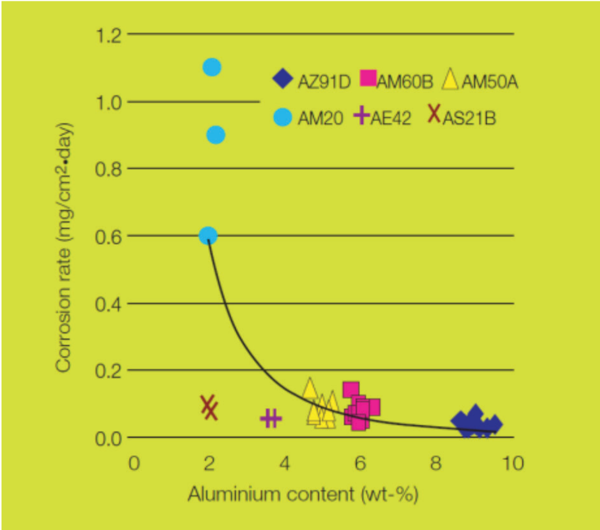


Figure 11 - Factors influencing the corrosion properties of magnesium alloys.



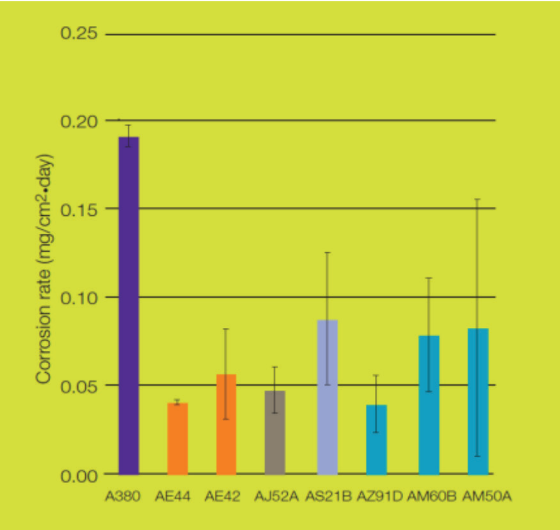


Figure 12 - Corrosion rate versus aluminum content for selected magnesium alloys. The test was done using die cast plates exposed to ASTM B117 salt spray for 240 hours.

Figure 13 - Corrosion rates in ASTM B117 salt spray (240 hours) for selected magnesium alloys and A380 aluminum alloy.

7.2 Galvanic Corrosion

Galvanic corrosion is an important consideration for magnesium, which is typically less noble than other metals used for structural applications. Notwithstanding this fact, proper precautions permit magnesium to be protected against galvanic corrosion. Galvanic corrosion occurs when magnesium is connected to other metallic materials in the presence of an electrolyte. Figure 14 shows the basis for galvanic corrosion for the case of bolting two magnesium castings together. The anode and cathode reactions must balance each other, which means that by reducing the consumption of electrons in the cathode reaction, the production of electrons in the anode reaction is reduced accordingly. The corrosion rate, I_{galv}, is proportional to the potential difference between the two metals in the assembly (E_c - E_a) and inversely proportional to some important resistances, R_c and R_e, as follows:

$$I_{galv} = (E_c - E_a)/ (R_c + R_e) \qquad (11)$$

E_c and E_a are the electrode potentials of the cathode and anode, respectively. R_c is the cathode polarisation resistance, which is a measure of how easily the cathode metal can consume electrons. High R_c means that the metal is a slow consumer of electrons, i.e., the cathode reaction rate is slow. R_e is the electrolyte resistance and is determined by the electrolyte resistivity, r, electrolyte cross-section (thickness), A, and distance between the anode and cathode, l, in Eq. (12).

$$R_e = r\ (l/A) \qquad (12)$$

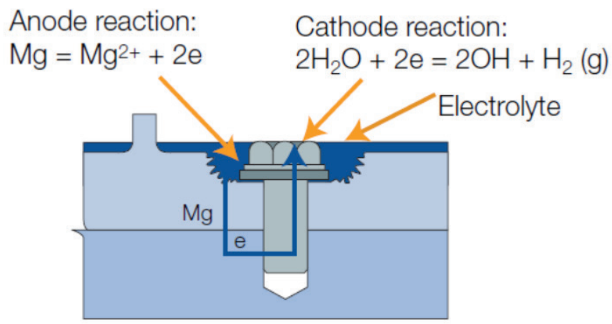


Figure 14 – Basis of galvanic corrosion.

The trend is that the most corrosion resistant alloys also show the lowest degree of galvanic corrosion, although tests have shown that there are minor differences between the various magnesium alloys concerning the extent of galvanic corrosion. The differences are small, meaning that the relative resistance to galvanic corrosion is not a decisive factor in alloy selection for a specific application. The properties of the cathode (other metal than magnesium) are far more important.

Galvanic corrosion protection is provided by proper material selection, proper selection of coatings and proper design, each of which is described below. A combination of these methods gives the optimum protection in a corrosive environment.

7.2.1 Compatible and Non-compatible Materials

The best selection is a material that provides a combination of low potential difference (E_c - E_a) and high cathode polarisation resistance, R_c. Such materials are much more compatible with magnesium. Table 21 gives an overview of compatible and non-compatible materials.

Table 21 - Compatible and non-compatible materials with magnesium die castings

Compatible materials	Non-compatible materials
Aluminum 5xxx and 6xxx series Tin Zinc Plastics and polymers	Steel and stainless steel Copper Nickel Titanium Selected aluminum alloys (e.g., 2xxx and A380)

7.2.2 Selective Use of Coatings

In order to improve the compatibility of magnesium with steel, e.g., the steel can be coated with either a selected metal plating or a polymer coating. Silicate sealed zinc plating has successfully been used on steel bolts for use with magnesium transfer cases. Older versions used a hexavalent chromium treatment, which since has been replaced with trivalent chromium for environmental reasons. Commercial versions of these coatings include Metex JS500™ and Metex JS2000™. Among the polymer coatings, nylon has shown very good performance; the same is the case with Xylan coating, which is a type of PTFE coating (Polytetrafluoroethylene or Teflon).

7.2.3 Proper Design

With proper design it is possible to influence the electrolyte resistance, (R_e), in Eq. (11). It is important to avoid electrolyte accumulation, and thus poor and improved design examples are given in Figure 15. Efficient drainage will reduce the electrolyte thickness and thus increase the electrolyte resistance, as seen from Eq. (12). Another method for increasing the electrolyte resistance is to insert spacers or shims as illustrated in Figure 15d. With an inert spacer of plastic, the distance between the two metals in the assembly, l_{galv} in Eq. (11), is increased. The effect of inert spacer thickness is shown in Figure 16a. The galvanic corrosion of magnesium is inversely proportional to the distance (from anode to cathode). Thus at a distance (thickness) of about 4.5 mm, there is no galvanic effect on the corrosion of magnesium. Even in service in a corrosive environment, this is a conservative value due to the very aggressive conditions of salt spray testing.

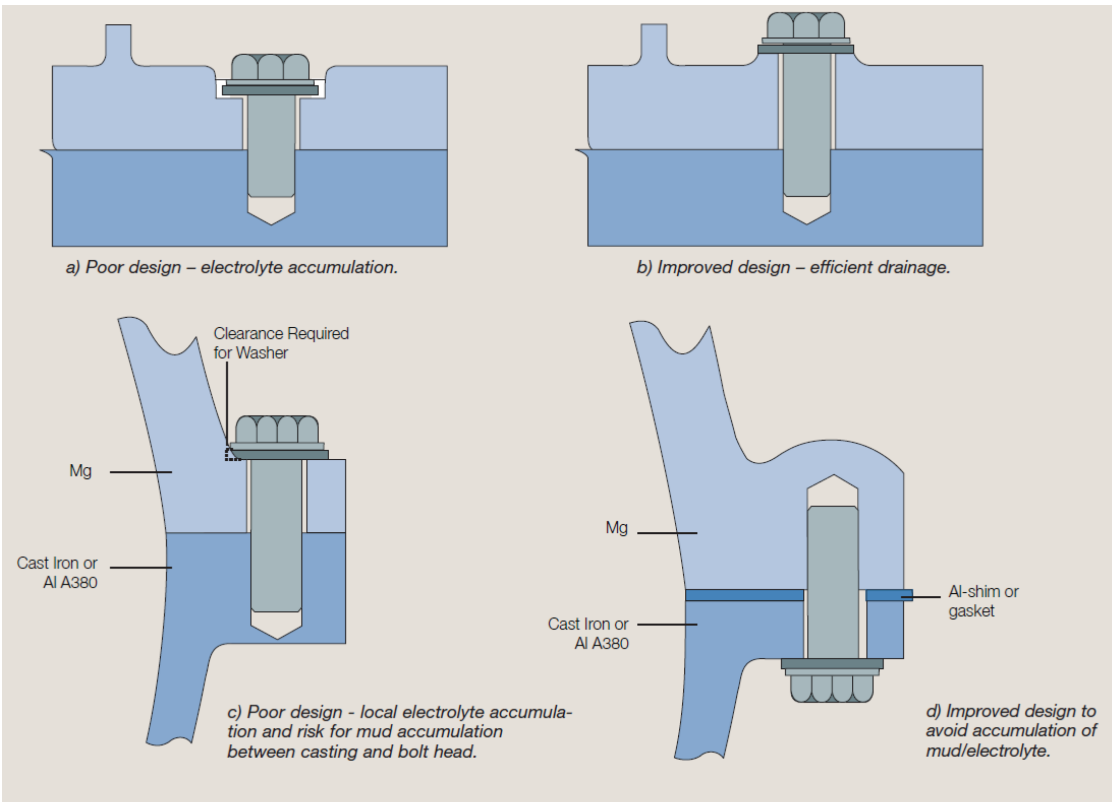
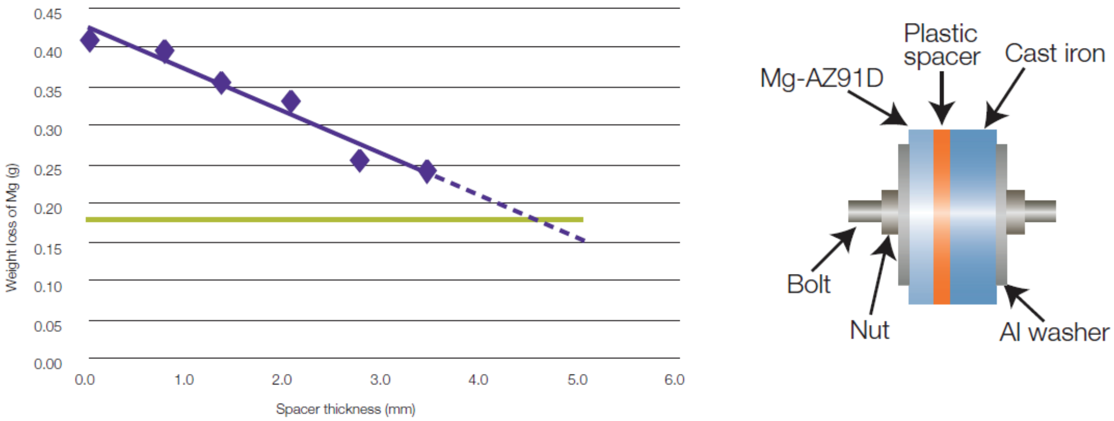


Figure 15 - Examples of poor and improved designs for galvanic corrosion protection.

In the case of an aluminum spacer or shim, a compatible material is inserted between magnesium and the metal that induces galvanic corrosion. The use of aluminum washers is very efficient, as displayed in Figure 16b. With an aluminum washer between the magnesium and the coated steel bolt, the galvanic corrosion is reduced to the same level as using aluminum bolts alone, i.e., the galvanic corrosion is fully controlled by the washer.



(a) (b)

Figure 16 - Effect of spacer distance on galvanic corrosion on AZ91D magnesium. The horizontal line represents non-galvanic corrosion of AZ91D. The test conditions were ASTM B117 salt spray for 200 hours.

When mud is accumulated at the bolt washer area, the effect of the washer is reduced but still gives a significant reduction compared to a plated steel bolt alone. The mud bridges the gap between the bolt head and magnesium, and the cathode reaction on the metal-plated bolt contributes more to the galvanic corrosion than with no mud present. It is expected that a polymer coating on the steel fasteners is better than metal plating in the presence of mud, because an intact and resistant polymer coating insulates the steel from the mud environment.

Bolt head design is also important for coated steel bolts. As described previously, it is important that the coating on the bolt is intact. During assembly, defects may easily have been made in the coating, and it is important that these defects are located as far as possible from the contact point to magnesium. Therefore, inner drive bolts are preferred over outer drive bolts. When outer drive bolts are used, flanged head bolts are recommended. Coatings over areas of the bolt head with sharp edges, as in hexagonal head bolts, have a tendency to become very thin or even absent. Therefore, it is recommended to select a bolt head design that is round and free from sharp edges. Examples of recommended bolt head designs for coated bolts are given in Figure 17. Coated steel fasteners with integrated aluminum washers are also available as seen in Figure 17d.

a) Recommended – Inner torx drive.

c) Not recommended – Hex head.

b) Recommended – Outer torx, flange head.

d) Recommended – Coated steel fasteners with integrated aluminium washers.

Figure 17 - Various bolt head designs and fasteners with integrated washers [5].

7.2.4 Coating of Magnesium

Coating the magnesium for protection against galvanic corrosion is not recommended. The reason is that coating defects are easily introduced during assembly and also during service. This defect in the coating on magnesium creates a small anodic area compared to the larger cathodic area, as illustrated in Figure 18. The corrosion rate on magnesium is proportional to the ratio of the cathode to anode areas. However, coating the magnesium may be essential for some automotive components such as front end supports and inner door frames. In such cases, robust coating systems, which can withstand the assembly forces as well as dynamic forces during service, must be used. Testing and practical experiences have shown that powder coating systems are the most robust coatings in this regard.

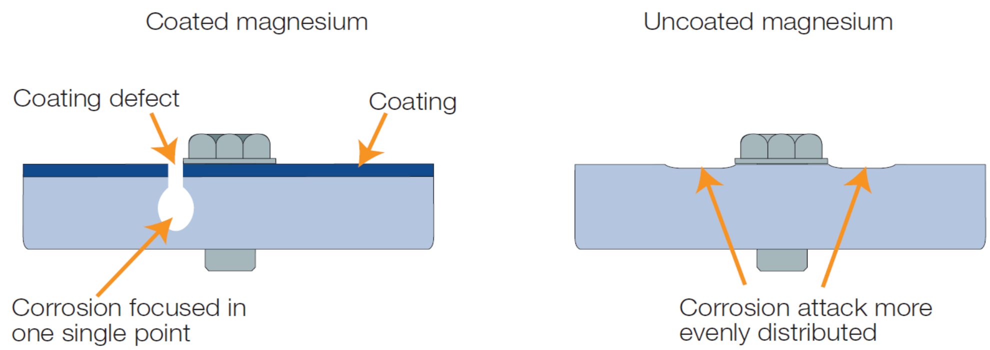


Figure 18 - Galvanic corrosion of coated and uncoated magnesium couples.

7.3 Surface Finishing

Finishing of magnesium die castings is done primarily for aesthetic purposes and is not needed for corrosion protection in typical ambient corrosion conditions. Figure 19 gives an overview of finishing options for magnesium die castings. The predominant finishing method is painting. Automotive components that are finished include frontend structures, inner door frames, valve covers and intake manifolds. The latter two are examples of components coated for aesthetic purposes. Other components that are surface finished include laptop computer housings, mobile phone housings, etc. Aesthetic appearance is also dominant for these components, but sometimes they are metal plated in order to provide improved contact over bare metal alone for electrical circuits. Hand power tool housings are also coated, primarily again for aesthetic purposes, but secondarily at times for corrosion protection.

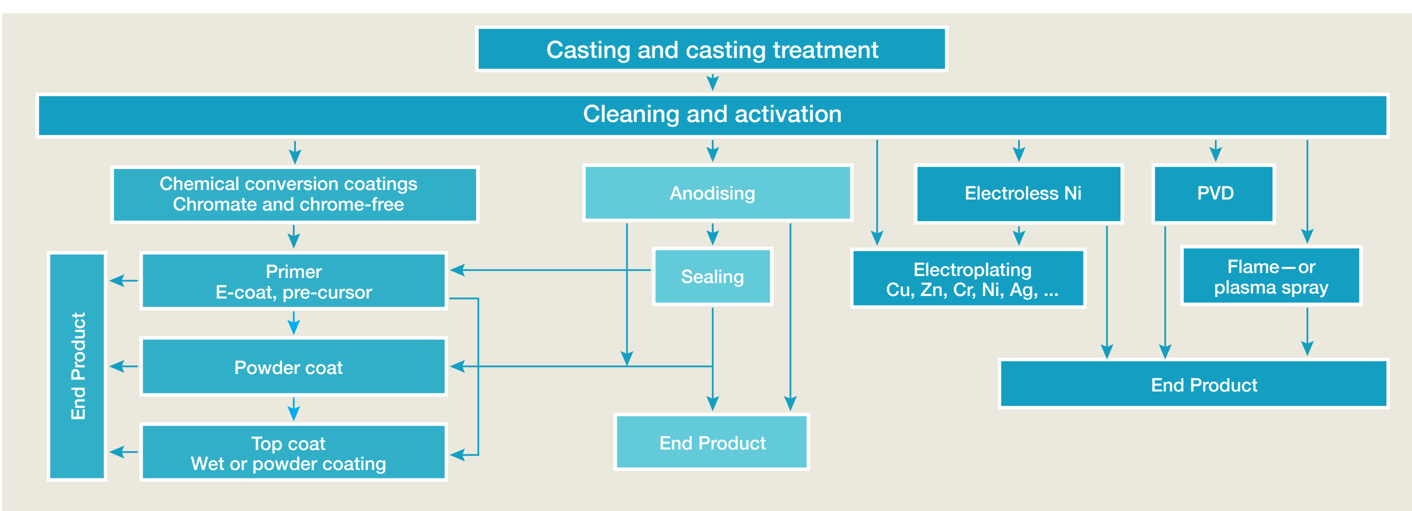


Figure 19 – Finishing options for magnesium die casting.

7.3.1 Pre-treatment of Magnesium

Pre-treatment of magnesium generally follows the process outlined in Figure 20. After machining and deburring, the die cast part is cleaned. Common practice is to use an alkaline cleaner; details of the cleaning will be described in the next section. Following the cleaning, there may be a pickling or etching process, although this step is sometimes omitted. The next step is normally the conversion coating itself; both dip and spray processes are used. Water rinsing normally occurs between the various steps, although some conversion coatings are no-rinse processes, i.e., there is no rinse after the conversion coating. The final rinse is often done using deionised water. After drying of the part, it is ready for application of the coating or the adhesive. This procedure is similar to the treatment sequence for other metals.

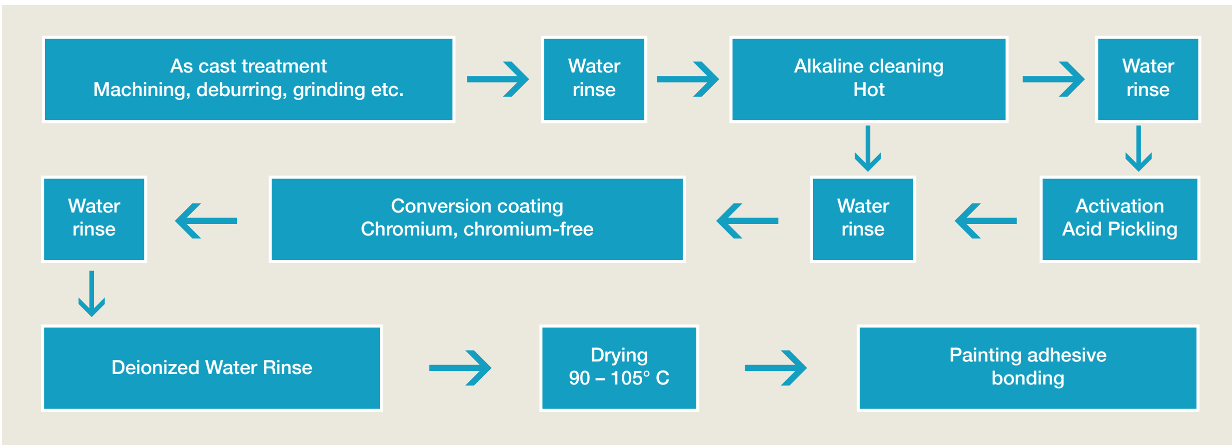


Figure 20 - Standard pre-treatment process for magnesium alloys.

7.3.2 Cleaning of Magnesium Die Castings

In any finishing process, cleaning of the casting in order to remove the residues of die lubricants, machining fluids and other contaminants is required. Otherwise these contaminants will interact with the subsequent treatments, likely resulting in failure of the coating or metal plating applied. Hot alkaline cleaners are commonly used, and sometimes these cleaners are combined with acid pickling in order to activate the surface for subsequent treatment. The need for activation is dependent on the process that follows; for example, the activation requirement is higher for chrome-free conversion coatings than for chromate, and even higher for surfaces that are to be metal plated.

The degree of etching of the magnesium in the cleaning process is dependent on the composition and pH of the cleaning agent. Generally, the etching rate decreases with increasing pH, and almost no etching occurs for cleaning agents with a pH above about 11. This is opposite to the cleaning of aluminum, where increasing pH of the cleaner increases the etching rate. Figure 21 displays the contrasting behaviour of magnesium and aluminum alloys in cleaning agents of various pH. The data also show variable, but not systematic, differences in the etching rate depending on whether spraying or immersion is used for the cleaning.

The International Magnesium Association (IMA) has published guidelines for acid mixtures suitable for pickling of magnesium alloys [12]. These mixtures include nitric acid, sulfuric acid, phosphoric acid, chromic acid, as well as hydrofluoric acid. The total etching can be from zero or negligible metal loss to as much as 50 μm for some mixtures. Generally, chromic and hydrofluoric acids give very little metal loss, while nitric, sulfuric and phosphoric acids give more metal loss. Figure 22 shows the etching effect of three commercial acid mixtures, one of which is an organic acid. The etching rate is from about 1 to 4 μm/min. Traditionally, magnesium die castings have been cleaned with an alkaline cleaner of high pH and then pickled in nitric acid.

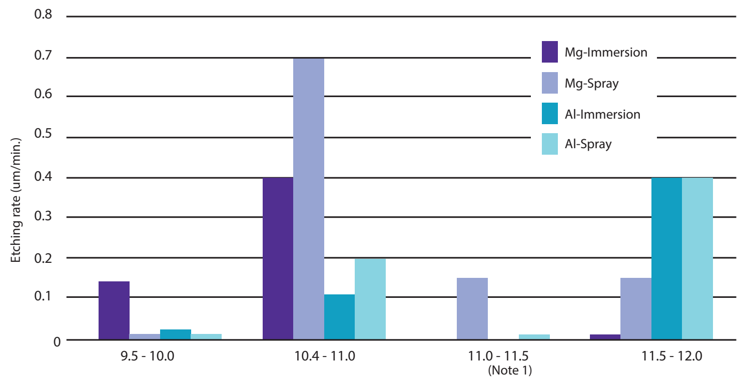


Figure 21 - Effect of cleaning agent pH on the etching rate on magnesium and aluminum [12]. Note 1: Cleaner contains silicate

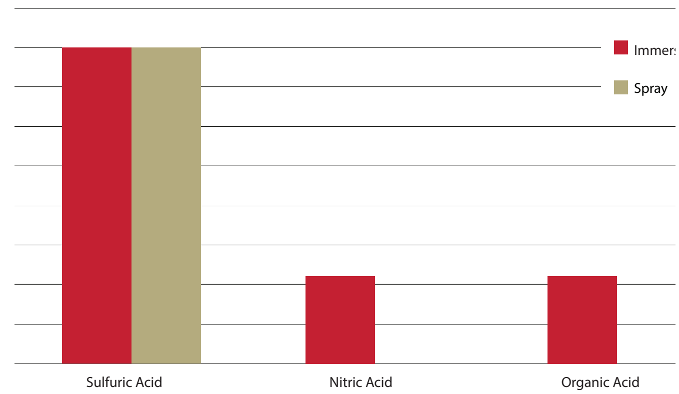


Figure 22 - Etching rates of selected commercial acid mixtures on magnesium die castings. The pH of the sulfuric and nitric acids was < 1.5, and for the organic acid 2.0 - 2.5 [12].

Sometimes the properties of die lubricants cause difficulties in their removal with conventional hot alkaline cleaners. The lubricants often contain various wax components, and the melting range of the wax components seem to be one of the important properties. Lubricants with wax components that start to melt or soften at a temperature lower than the temperature of the cleaning bath are easier to remove than those with wax components that melt/soften at higher temperatures. It was also found that lubricant residues were preferentially located at positions on the castings where melt fronts meet. On casting surfaces created by fragmented melt flow, the locations of residues were not as well defined.

7.3.3 Conversion Coatings

The chrome-free conversion coatings include:

- Complex fluoro-compounds based on zirconium and/or titanium. Polymer additives may also be incorporated into the film
- Phosphate solutions
- Phosphate-permanganate solutions
- Mixed solutions of vanadate, manganate and molybdate
- Silane solutions
- Cerate solutions

The chrome-free conversion coatings promote the adhesion of polymer coatings, but except for those with vanadate or molybdate, they do not have the self-healing and inhibiting effect of chromate films. Despite this lack of extra corrosion protection, these treatments show performance similar to chromate treatments in accelerated corrosion tests. This is illustrated in Figure 23 using complex titanium- and zirconium hexafluoride as examples. The samples have been exposed to test procedure VDA 621-415 for three weeks, and the quality is evaluated using corrosion creep from a pre-made scribe and stone chipping according to VDA 621-427. The quality is dependent on the cleaning and pickling procedure used. An etching cleaner with pH 9.5-10 gives better quality than non-etching cleaners with higher pH. The combination of a silicate-containing cleaner and a chrome-free conversion coating does not give very good results, even though the etching rate of the silicate-containing cleaner is the same as the cleaner with pH 9.5-10 (see Figure 19). In order to obtain the same quality with the chrome-free as the chromate treatment, pickling must be included. Hence, the optimum combination seems to be a cleaner with pH around 10 and an acid pickling before the chrome-free conversion coating.

Cleaner	pH = 9.5 - 10.0 Immersion	pH = 11.5 - 12.0 Immersion	pH = 11.0 – 11.5 Spray (Note 1)	pH = 9.5 - 10.0 Immersion	pH = 9.5 - 10.0 Immersion
Pickling	None			Nitric acid	None
Conversion coating	Complex zirconium – and titanium hexafluoride				Chromate

Figure 23 - Images of samples with different combinations of cleaning, pickling and conversion coatings after three weeks in VDA 615-415 test. The coating system is lead-free E-coat (Cathoguard 400 from BASF). (Note 1) cleaner contains silicate.

The effect of cleaning and pickling is also valid for the other chrome-free conversion coatings, as illustrated in Figure 24. When no pickling is used, the chromate treatment performs better than the chrome-free, but when pickling is added to the process, the chrome-free treatments show similar performance to the chromate. This is especially evident for the silane treatment, which shows very poor performance in the absence of pickling, but with pickling a performance similar to chromate. The chrome-free treatments seem to display a similar efficiency whether used on AZ or AM magnesium alloys, as shown in Figure 25. The chrome-free alternatives are also efficient for powder coatings, as seen from Figure 26. However, the compatibility between specific powder coatings and the conversion coating must be tested before selection for a given application.

Besides careful cleaning and pickling, drying after application of the conversion coating is important. The quality is better when the substrate is dried before application of the paint, rather than applying the paint just after the final rinse with no intermediate drying. Selected commercial, chrome-free conversion coatings are listed in Table 22. These treatments have shown performance similar to chromate in various accelerated corrosion tests. Care must be taken to choose a conversion coating suitable for the alloy substrate as some conversion coatings rely on the presence of > 5% aluminium in the surface layers, so they may be effective on die castings in AM50, AM60 and AZ91 but not for AZ31B or other wrought alloys. Alloys containing rare earths, particularly yttrium and no aluminium require special conversion coatings.

Other products are available, but it is not possible to give a complete list. Some products are also sold under different trade names in Europe and North America.

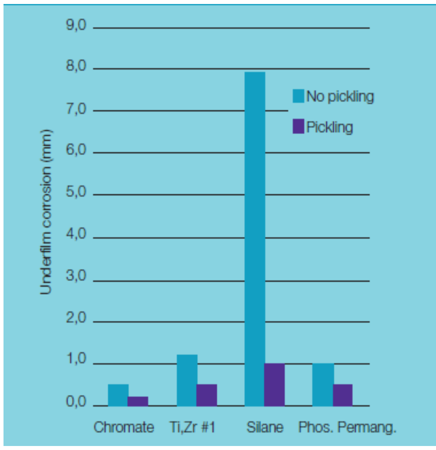


Figure 24 - *Effect of pickling on underfilm corrosion from a scribe on AZ91D with various conversion coatings. The test was done according to VDA-621-415 (3 cycles).*

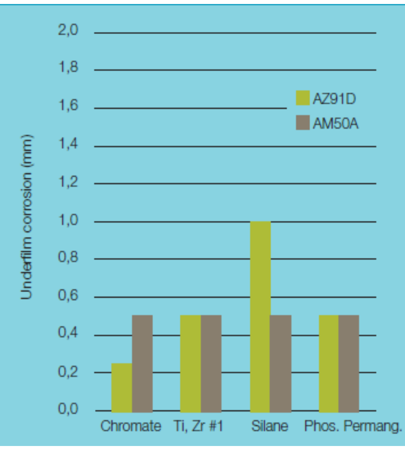


Figure 25 - *Effect of alloy on underfilm corrosion from a scribe on samples with various conversion coatings. The test was done according to VDA-621-415 (3 cycles).*

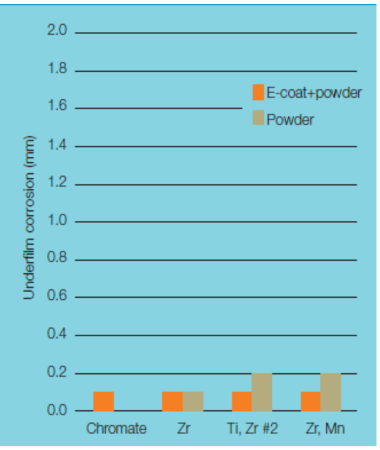


Figure 26 - *Underfilm corrosion of AZ91D with chromate and chrome-free conversion coatings plus powder coatings with and without E-coat.*

Table 22 - *Selected commercial, chrome-free conversion coatings for magnesium components*

Name	**Supplier**	**Type of coating**
Magpass™	AHC Oberflächentechnik GmbH	Mixed solution of vanadate, molybdate and maganate
Gardobond™X4707 Gardobond™X4740 Gardobond ™X4729	Chemetall GmbH	Titanium/zirconium hexafluoride Zirconium hexafluoride Suitable for Y containing alloys
Alodine™5200 Alodine™4850 Alodine™400 Alodine™160	Henkel Technologies – now being sold under the Bonderite Trade name rather than Alodine.	Composite film with Ti and/or Zr oxyfluoro compounds with polymer additions Zr and fluoride compounds with Mn oxides

7.3.4 Anodizing

Anodizing is an alternative treatment, which can be used as a final finish or as a base for subsequent painting. In anodizing, magnesium is the anode in an electrochemical cell. High voltage is applied, and magnesium is dissolved into magnesium ions. These ions combine with ions in the electrolyte (bath) and thus enhance the natural oxide film by forming either $Mg(OH)_2$ or MgO. Other constituents in the electrolyte can be incorporated into the film (for example chromate, phosphate, silicate and fluoride). Some processes utilise very high voltage, resulting in spark discharge taking place on the magnesium surface, forming a ceramic-like film.

Anodizing gives excellent corrosion resistance, as well as improved resistance to wear. Figure 27 shows the behaviour of various anodic coating treatments after 80 days in the cyclic GM9540P test. In all cases, there is no corrosion attack at the scribe and only minor attack on the rest of the surface. The paint adhesion is also generally very good, as illustrated in Figure 27e. Again, no corrosion from the scribe is found after the 80 days in the test environment.

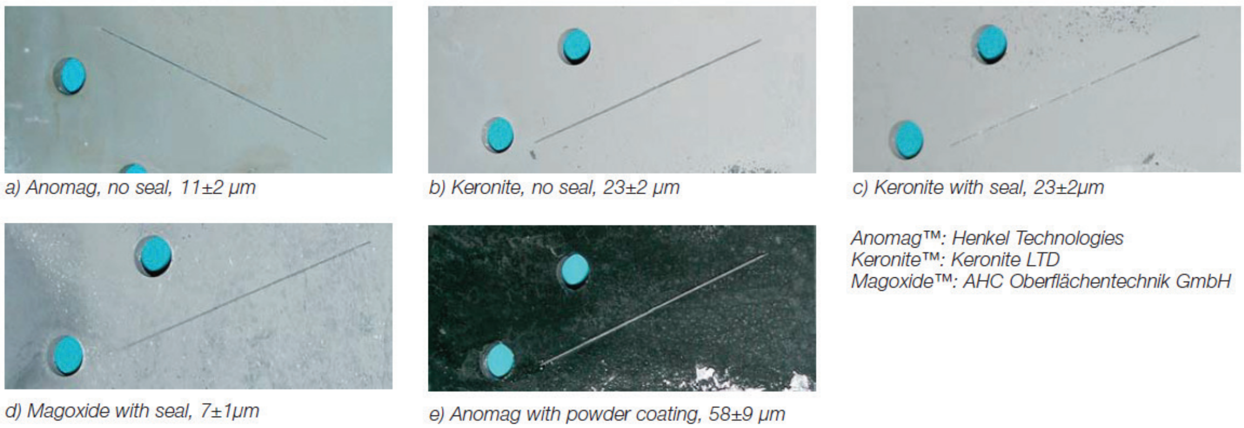


Figure 27 - Selected anodizing coatings after exposure to GM9540P-cycle B for 80 days.

Although not illustrated here Tagnite™ from Technology Applications Group, and Bonderite™ MgC from Henkel have been shown to offer similar performance.

7.3.5 Painting

Painting of magnesium is similar to that of other metals. The paint is often applied over a conversion coating, as described in the previous section.

The build-up of the paint system is dependent on the requirements and the purpose of the coating system. On some applications, a single E-coat primer can be used, or more commonly as a single layer in advance of powder coating. For more demanding applications, there may be a combination of a selected primer and powder coating. When a very high quality finish is required, it may even be a base coating providing the color and a clear top coat. Examples of coating systems and typical coating thicknesses are given in Figure 28. E-coats without lead, which are more environmentally friendly than conventional E-coats, have also proven to be efficient for magnesium.

For decorative surfaces, painting is a challenge due to casting defects such as porosity and cold flows as well as the naturally occurring depressions found on castings. Castings also have a rougher surface than sheet material. Interconnected porosity in some die castings may cause pinholes in the paint because of gas escaping from the pores during curing of the paint at elevated temperatures. Often castings require the use of filling and sanding in order to meet the cosmetic requirements. Special anti-bubble grade paints that are designed to give delayed curing (thus allowing the gas to escape before the end of curing) may prevent the formation of pinholes. Other preventative methods are as follows:

- Preheat the castings to a higher temperature than the paint curing temperature.
- Lower the curing temperature and increase the curing time.
- Start the curing at a lower temperature and finish at a higher temperature.

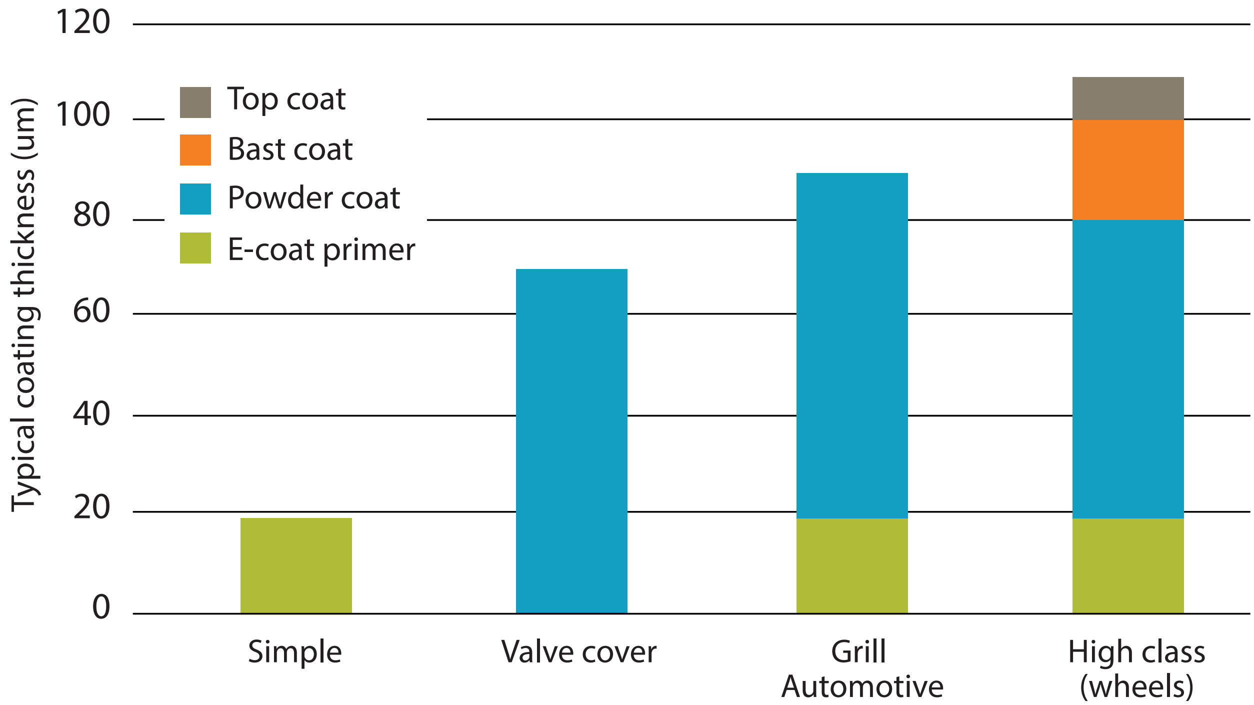


Figure 28 - Examples of coating systems used on magnesium die castings.
The majority of parts, including almost all interior components, do not require any coating.

Decorative painting of magnesium die casting is successfully done for components such as computers, cameras, and electronic equipment. These thin wall castings exhibit fewer problems with rib structures, porosity and casting defects described-above. Furthermore, the industry has adapted some of the recommendations for painting castings, especially using textured paint to hide any casting defects.

7.3.6 Metal Plating

Magnesium die castings can be metal plated in a manner similar to aluminum. The outline of the plating process is given in Figure 29. The cleaning and activation steps (acid and alkaline) are needed to remove the die lubricant and to provide a uniform and reactive surface for initial plating, whether it be zincating or electroless nickel. Zincating is an electrolytic zinc deposition process giving a 0.1 -0.2 µm layer of zinc on the surface. In traditional processes, the zincating is followed by electrolytic deposition of copper (copper strike) from a cyanide copper bath. On top of the copper, any metal can be plated (chromium, silver, nickel, gold). Detailed procedures for such processes are found in [12].

Processes for the direct application of electroless nickel are also available today, as indicated in Figure 27. Electroless nickel can replace both the zincating and the copper strike steps to provide a surface for plating of other metals, or it can serve as the final finish. As indicated in Figure 26, electroless nickel can also be combined with the copper strike, either on top of the copper strike or as a base for the copper strike.

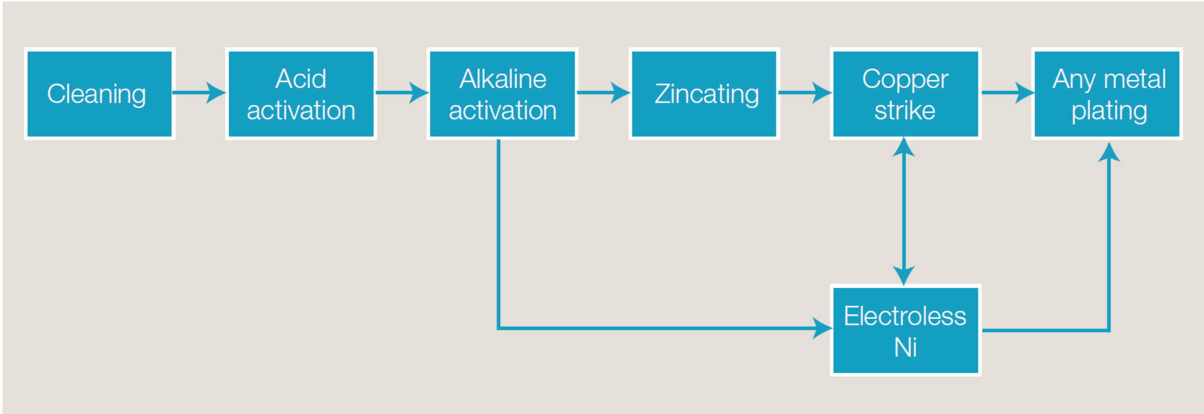


Figure 29 - *Typical process for plating of magnesium.*

Plating of magnesium alloys that contain more than about 7% Al becomes more difficult than for lower aluminum compositions. This challenge has been met on numerous occasions, however, such that AZ91D components (e.g., electronic housings) are successfully metal plated. Additionally, many processes in this field are proprietary, and detailed procedures are not published. While successful metal plating gives a high quality finish, galvanic corrosion between the more noble metals used for plating and the magnesium is a concern in certain environments.

7.4 Storage Protection

For some critical applications, corrosion protection of magnesium components during transport and storage may be needed. Several methods and products are available:

- Store in sealed containers with a desiccant. The desiccant can be omitted if the parts are packed in dry atmospheres, for example, at relative humidity below 70% and room temperature.
- Apply an oil or wax coating. Many proprietary products are available, but it is recommended to test the effectiveness before large-scale use of any particular product.
- Utilize conversion coatings. Most conversion coatings will give adequate protection under normal storage conditions, but may become ineffective as a paint base after long time storage in humid conditions.

8. Summary and Concluding Remarks

As the lightest structural metal, magnesium offers a good combination of physical and mechanical properties and a higher mass saving potential compared to advanced high-strength steel (AHSS), aluminum, polymers, and glass fiber reinforced polymers (GFRP) for equal stiffness or strength. While carbon fiber reinforced polymers (CFRP) has the highest mass saving potential, wrought magnesium alloys offer slightly less mass saving but at a lower cost. While the room temperature mechanical properties of most magnesium alloys are comparable to other structural materials but, with the exception of creep resistant sand casting alloys used in aerospace applications, magnesium is generally not recommended for applications at temperatures above 150°C.

While the general corrosion of magnesium alloys is comparable to (or slightly better than) that of aluminum alloys, galvanic corrosion is a major concern when magnesium is in contact with dissimilar materials. Proper material selection, selective use of coating on cathode materials and proper design are the key factors to protect against galvanic corrosion. The optimum choice for fasteners in a corrosive environment is either aluminum (6xxx series) or coated steel with an aluminum washer or spacer (5xxx or 6xxx series). Numerous commercial chrome-free conversion coatings are available for magnesium, and painting is the predominant finishing method for magnesium and is usually done for decorative purposes. Commercial metal plating processes that give a high quality finish are also available.

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References

1. A. Beck, *The Technology of Magnesium and its Alloys*, Pub: F.A. Hughes Company, 1943.
2. G.V. Raynor, *Physical Metallurgy of Magnesium and its Alloys*, Pergamon Press, 1959.
3. E.F. Emley, *Principles of Magnesium Technology*, Pergamon Press, 1966.
4. *Magnesium and Magnesium Alloys*, ASM Speciality Handbook, Published by ASM International, 1999.
5. ASTM International, *Standard Specification for Magnesium Alloys in Ingot Form for Sand Castings, Permanent Mold Castings, and Die Castings*, B93/B91M-15, 2015.
6. ASTM International, *Standard Specification for Magnesium-Alloy Extruded Bars, Rods, Profiles, Tubes, and Wire*, B107/B107M-13, 2013.
7. ASTM International, *Standard Specification for Magnesium-Alloy Sheet and Plate*, B90/B90M-15, 2015.
8. Magnesium Elektron, *Elektron Wrought Alloys*, Datasheet 441.
9. Meridian Lightweight Technologies LLC, *Materials Properties*, Technical Data Sheet, 2006.
10. A.A. Luo, *Magnesium: Current and Potential Automotive Applications*, JOM Journal of Metals, 2002, 54, (2), pp. 42-48.
11. Hydro Magnesium, *Corrosion and Finishing of Magnesium Alloys*, Technical Brochure, 2006.
12. International Magnesium Association, *Surface Finishes for Magnesium*, Technical Brochure, 1989.
13. POSCO, *Magnesium Sheet*, 2018.

International
Magnesium
Association
1000 Westgate Drive, Suite 252
Saint Paul, Minnesota 55114 USA
Phone: +1 651-379-7305
Fax: +1 651-290-2266
www.intlmag.org