CHAPTER 7
MAGNESIUM AND ITS ALLOYS

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7.1 INTRODUCTION

Magnesium, with a specific gravity of only 1.74, is the lowest-density metal available for engineering use. It is produced either by electrolytic reduction of $MgCl_2$ or by chemical reduction of MgO by Si in the form of ferrosilicon. $MgCl_2$ is obtained from seawater, brine deposits, or salt lakes. MgO is obtained principally from seawater or dolomite. Because of the widespread, easy availability of magnesium ores (e.g., from the ocean), the ore supply is, in human terms, inexhaustible.

7.2 USES

Magnesium is used both as a structural, load-bearing material and in applications that exploit its chemical and metallurgical properties.

7.2.1 Nonstructural Applications

Because of its high place in the electromotive series, magnesium is used as a sacrificial anode to protect steel from corrosion; some examples are the protection of buried pipelines and the prolongation of the life of household hot-water tanks. Alloys used for this purpose are produced by permanent-mold castings and by extrusion.

Magnesium in powder form is added to gray cast iron to produce ductile, or nodular, iron, an alloy that has many of the producibility advantages of cast iron but is ductile and strong.

A significant use for magnesium powder is its addition to the iron tapped from blast furnaces to remove sulfur prior to converting to steel, thereby increasing the efficiency of the blast furnace and improving the toughness of the steel.

Magnesium powder is also used to produce the Grignard reagent, an organic intermediate used in turn to produce fine chemicals and pharmaceuticals.

Magnesium sheet and extrusions are used to produce photoengravings.

Magnesium in ingot form is one of the principal alloying additions to aluminum, imparting improved strength and corrosion resistance to that metal.

7.2.2 Structural Applications

Magnesium structures are made from sand, permanent-mold, investment, and die casting, and from sheet, plate, extrusions, and forgings. The base forms produced in these ways are fabricated into

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finished products by machining, forming, and joining. Finishing for protective or decorative purposes is by chemical-conversion coatings, painting, or electroplating.

The most rapidly growing method of producing structural parts is die casting. This method is frequently the most economical to produce a given part and is especially effective in producing parts with very thin sections. A stimulus for the recent very high growth rate has been the development of a high-purity corrosion-resistant alloy that makes unnecessary the protective finishing of many parts. See alloy AZ91D in Table 7.1. Die castings are produced by cold chamber, by hot chamber, and by a recently developed method analogous to the injection molding of plastic parts. The latter technique, known as Thixomolding,[1,2,3,4] uses a machine that advances the alloy in a semisolid state by means of a screw and then injects an accumulated amount into the die. The melting step is eliminated, production rates are at least as high as for hot-chamber die casting, and metal quality is superior to that produced by either cold- or hot-chamber die casting. Two major fields dominate the die-casting markets: automotive (e.g., housings, brake pedals, transmissions, instrument panels) and computers (e.g., housings, disc readers).

Those properties mainly significant for structural applications are density (automotive and aerospace vehicle parts; portable tools such as chain saws; containers such as for computers, cameras, briefcases; sports equipment such as catcher's masks, archery bows); high damping capacity (antivibration platforms for electronic equipment; walls for sound attenuation); excellent machinability (jigs and fixtures for manufacturing processes); high corrosion-resistance in an alkaline environment (cement tools).

7.3 ALLOYS AND PROPERTIES

Many alloys have been developed to provide a range of properties and characteristics to meet the needs of a wide variety of applications. The most frequently used are given in Table 7.1. There are two major classes—one containing aluminum as the principal alloying ingredient, the other containing zirconium. Those containing aluminum are strong and ductile, and have excellent resistance to atmospheric corrosion. Since zirconium is a potent grain refiner for magnesium alloys but is incompatible with the presence of aluminum in magnesium, it is added to all alloys not containing aluminum. Within this class, those alloys containing rare earth or yttrium are especially suited to applications at temperatures ranging to as high as 300°C. Those not containing rare-earth or yttrium have zinc as a principal alloying element and are strong, ductile, and tough.

Recently, the high-purity casting alloys, AZ91E for sand and permanent mold castings and AZ91D, AM60B, AM50A, and AS41B for die castings, have been developed. The high-purity die casting alloys are superior in corrosion resistance to the commonly used aluminum die casting alloy. These alloys have been largely responsible for the large expansion in magnesium automotive applications.

7.3.1 Mechanical Properties of Castings

Magnesium castings are produced in sand, permanent, investment, pressure die-casting molds.

Castings produced in sand molds range in size from a few pounds to a few thousand pounds and can be very simple to extremely complex in shape. If production runs are large enough to justify higher tooling costs, then permanent instead of sand molds are used. The use of low pressure to fill a permanent mold is a low-cost method that is also used. Investment casting is a specialized technique that permits the casting of very thin and intricate sections with excellent surface and high mechanical properties. Die casting is a process for the production of castings with good dimensional tolerances, good surface, and acceptable properties at quite low cost.

Mechanical properties of cast alloys are given in Table 7.2.

7.3.2 Mechanical Properties of Wrought Products

Wrought products are produced as forgings, extrusions, sheet, and plate. Mechanical properties are given in Table 7.3.

7.3.3 Physical Properties

A selection of physical properties of pure magnesium is given in Table 7.4. Most of these are insensitive to alloy addition, but melting point, density, and electrical resistivity vary enough that these properties are listed for alloys in Table 7.5.

7.4 FABRICATION

7.4.1 Machining

Magnesium is the easiest of all metals to machine: it requires only low power and produces clean, broken chips, resulting in good surfaces even with heavy cuts.

7.4.2 Joining

All standard methods of joining can be used, including welding, riveting, brazing, and adhesive bonding.

Table 7.1 Magnesium Alloys in Common Use

ASTM Designation	Ag	Al	Fe max	Mn	Ni max	Rare Earth	Si	Zn	Zr	Forms
AM50A		4.9	0.004	0.32	0.002			0.22		DC
AM60B		6.0	0.005	0.42	0.002			0.22max		DC
AS41B		4.2	0.0035	0.52	0.002		1.0	0.12		DC
AZ31B		3	0.005	0.6	0.005			1		S, P, F, E
AZ61A		6.5	0.005	0.33	0.005			0.9		F, E
AZ80A		8.5	0.005	0.31	0.005			0.5		F ,E
AZ81A		7.6		0.24				0.7		SC, PM, IC
AZ91D		9	0.005	0.33	0.002			0.7		DC
AZ91E		9	0.005	0.26	0.0010			0.7		SC. PM
EZ33A						3.2		2.5	0.7	SC, PM
K1A									0.7	SC, PM
M1A				1.6						E
QE22A	2.5					2.2			0.7	S, PM, IC
WE43A			0.01	0.15	0.005	A		0.20	0.7	S, PM, IC
WE54A				0.15	0.005	B			0.7	S, PM, IC
ZE41A				0.15		1.2		4.2	0.7	S, PM, IC
ZE63A						2.6		5.8	0.7	S, PM, IC
ZK40A								4	0.7	E
ZK60A								5.5	0.7	F, E

A = 4 Yttrium; 3 RE
B = 5.1 Yttrium; 4 R.E.
DC = die casting; E = extrusion; F = forging; IC = investment casting; P = plate; PM = permanent mold; S = sheet; SC = sand casting

Table 7.2 Typical Mechanical Properties for Castings

Alloy	Temper	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation in 2 in. (%)
Sand and Permanent Mold Castings				
AZ81A	T4	276	85	15
AZ91E	F	165	95	3
	T4	275	85	14
	T6	275	195	6
EZ33A	T5	160	105	3
K1A	F	185	51	20
QE22A	T6	275	205	4
WE43A	T6	235	190	4
WE54A	T6	270	195	4
ZE63A	T6	295	190	7
Investment Castings				
AZ81A	T4	275	100	12
AZ91E	F	165	100	2
	T4	275	100	12
	T5	180	100	3
	T7	275	140	5
EZ33A	T5	255	110	4
K1A	F	175	60	20
QE22A	T6	260	185	4
Die Castings				
AM50A	F	200	110	10
AM60B	F	220	130	8
AS41B	F	210	140	6
AZ91D	F	230	160	3

Table 7.3 Typical Mechanical Properties of Wrought Products

Alloy	Temper	Tensile Strength (MPa)	Yield Strength (MPa)		Elongation in 2 in. (%)
			Tensile	Compressive	
Sheet and Plate					
AZ31B	O	255	150	110	21
	H24	290	220	180	15
Extrusions					
AZ31B	F	260	200	95	15
AZ61A	F	310	230	130	16
AZ80A	F	340	250	140	11
	T5	380	275	240	7
M1A	F	255	180	125	12
ZK40A	T5	275	255	140	4
ZK60A	F	340	250	185	14
	T5	365	305	250	11
Forgings					
AZ31B	F	260	195	85	9
AZ61A	F	195	180	115	12
AZ80A	F	315	215	170	8
	T5	345	235	195	6
	T6	345	250	185	5
ZK60A	T5	305	205	195	16
	T6	325	270	170	11

Welding is by inert-gas-shielded processes using either helium or argon, and either MIG or TIG. Alloys containing more than 1.5% aluminum should be stress-relieved after welding in order to prevent stress-corrosion cracking due to residual stresses associated with the weld joint. Rivets for magnesium are of aluminum rather than magnesium. Galvanic attack is minimized or eliminated by using aluminum rivets made of an alloy high in magnesium, such as 5056. Brazing is used, but not extensively, since it can be done only on alloys with a high melting point, such as AZ31B or K1A. Adhesive bonding is straightforward, and no special problems related to magnesium are encountered.

7.4.3 Forming

Magnesium alloys are formed by all the usual techniques, such as deep drawing, bending, spinning, rubber forming, stretch forming, and dimpling.

In general, it is preferable to form magnesium in the temperature range of 150–300°C. While this requires more elaborate tooling, there is some compensation in the ability to produce deeper draws (thus fewer tools) and in the elimination or minimizing of springback. Hydraulic rather than mechanical presses are preferred.

Table 7.4 Physical Properties of Pure Magnesium

Density	1.718 g/cm^3 (Ref. 5)
Melting point	650°C (Ref. 6)
Boiling point	1107°C (Ref. 6)
Thermal expansion	25.2×10^{-6}/K (Ref. 7)
Specific heat	1.025 kJ/kg·K at 20°C (Ref. 8)
Latent heat of fusion	360–377 kJ/kg (Ref. 8)
Latent heat of sublimation	6113–6238 kJ/kg Ref. 6)
Latent heat of vaporization	5150–5400 kJ/kg (Ref. 6)
Heat of combustion	25,020 kJ/kg (Ref. 10)
Electrical resistivity	4.45 ohm meter $\times 10^{-8}$
Crystal structure	Close-packed hexagonal: a + 0.32087 nm; c = 0.5209 nm; c/a = 1.6236 (Ref. 9)
Young's modulus	45 Gpa
Modulus of rigidity	16.5 Gpa
Poisson's ratio	0.35

Table 7.5 Physical Properties of Alloys[10]

Alloy	Density (g/cm^3)	Melting Point (°C) Liquidus	Melting Point (°C) Solidus	Electrical Resistivity (ohm-metres × 10^{-8})
AM60B	1.79	615	540	
AS41B	1.77	620	565	13.0
AZ31B	1.77	632	605	9.2
AZ61A	1.8	620	525	12.5
AZ80A	1.8	610	490	15.6
AZ81A	1.80	610	490	13.0
AZ91D	1.81	595	470	17.0
EZ33A	1.83	645	545	7.0
K1A	1.74	649	648	5.7
M1A	1.76	649	648	5.4
QE22A	1.81	645	545	6.8
ZK60A	1.83	635	520	5.7

7.5 CORROSION AND FINISHING

Magnesium is highly resistant to alkalies and to chromic and hydrofluoric acids. In these environments, no protection is usually necessary. On the other hand, magnesium is less resistant to other acidic or salt-laden environments. While most magnesium alloys can be exposed without protection to dry atmosphere, it is generally desirable to provide a protective finish.

Magnesium is anodic to any other structural metal and will be preferentially attacked in the presence of an electrolyte. Therefore, galvanic contact must be avoided by separating magnesium from other metals by the use of films and tapes. These precautions do not apply in the case of 5056 aluminum alloy, since the galvanic attack in this case is minimal.

Because magnesium is not resistant to acid attack, standing water (which will become acidic by absorption of CO_2 from the atmosphere) must be avoided by providing drain holes.

7.5.1 Chemical-Conversion Coatings

There are a large number of chemical-conversion processes based on chromates, fluorides, or phosphates. These are simple to apply and provide good protection themselves, in addition to being a good paint base.

7.5.2 Anodic Coatings

There are a number of good anodic coatings that offer excellent corrosion protection and also provide a good paint base.

7.5.3 Painting

If a good chemical-conversion or anodic coating is present, any paint will provide protection. Best protection results from the use of baked, alkaline-resistant paints.

7.5.4 Electroplating

Once a zinc coating is deposited chemically, followed by a copper strike, standard electroplating procedures can be applied to magnesium to give decorative and protective finishes.

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