Light Metals
Lecture 19: Magnesium

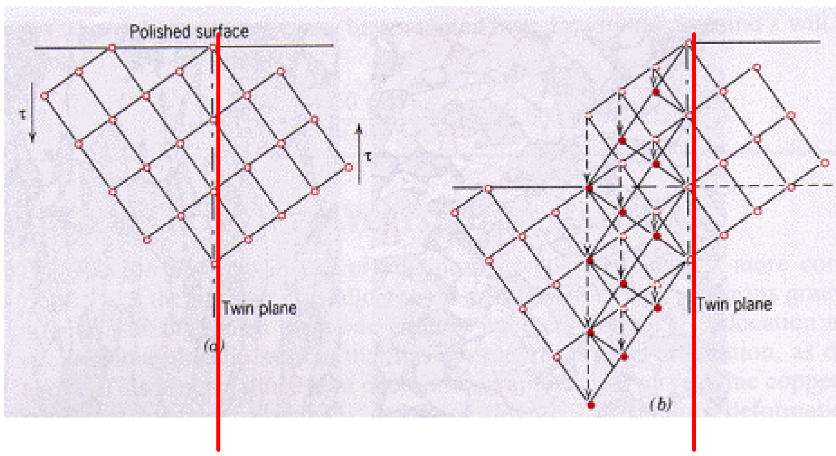
MMat 380

Twinning

A shear force which causes atomic displacements such that the atoms on one side of a plane (twin boundary) mirror the atoms on the other side

Displacement magnitude in the twin region is proportional to the atom's distance from the twin plane

Twinning



Twinning

- Co-ordinated movement of atoms that leads to a
- re-orientation of a part of the crystal
- Small amount of deformation as compared to slip
- Occurs in metals with BCC or HCP structures

Twinning

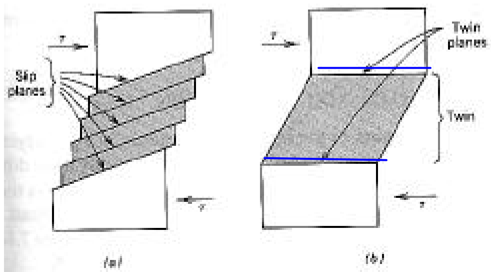
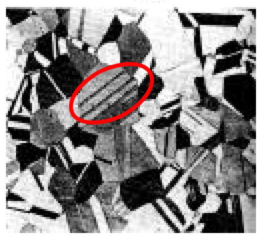


FIGURE 7.13 For a single crystal subjected to a shear stress τ, (a) deformation by slip; (b) deformation by twinning.

Schematic from Callister



Micrograph of twinning in phosphor bronze

Comparison of slip and twinning

Slip	Twinning
Orientation of the atoms remains the same	Reorientation of atomic direction across twin plane
Displacement takes place in exact atomic spacings	Atomic displacement is less than interatomic spacing

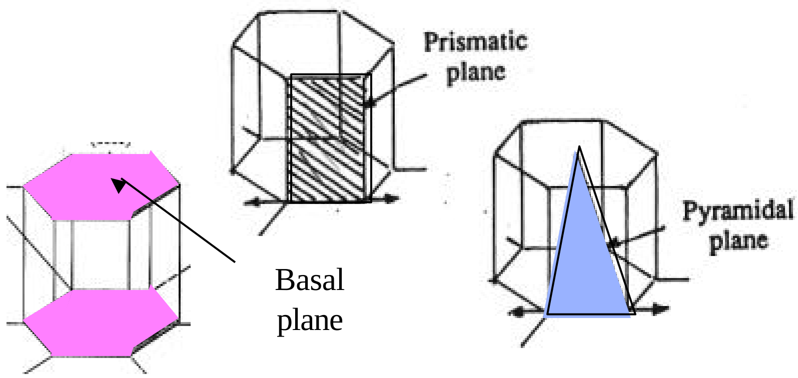
Outline

- General properties
- Advantages and disadvantages
- Uses
- Alloy systems
- High temperature castings

Magnesium

- Melting point 650°C
- Density 1.74 gm/cm^3
- HCP crystal structure (Mg alloys difficult to plastically deform at room temperature)
- Mg usually used in the form of castings
- Reactive metal – readily oxidizes
- Excellent machinability
- Poor corrosion resistance – needs protection especially near salt H_2O

Principal Deformation Planes in the Mg Unit Cell



@ room temperature

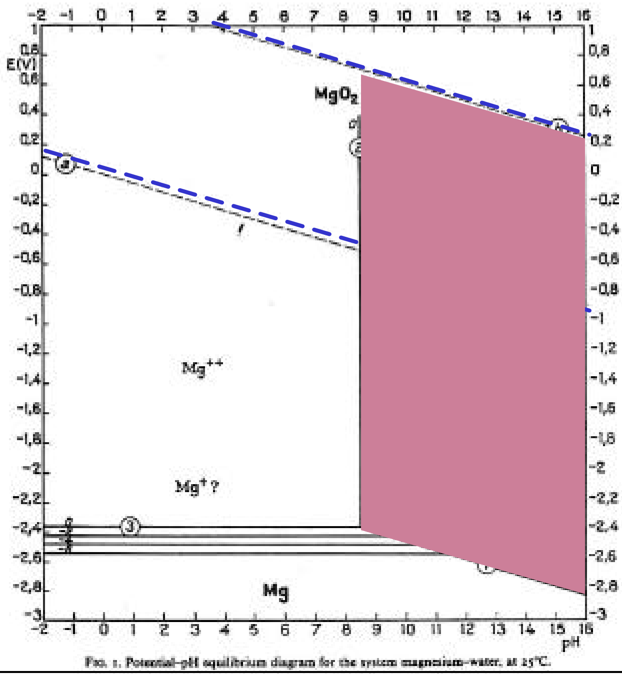
Advantages and Disadvantages

Advantages

- Excellent machinability
- Good castability
- Extremely light
- High thermal conductivity
- Good weldability
- Excellent strength/weight ratio
- Good creep resistance

Disadvantages

- High cost
- Poor corrosion resistance
- High electrochemical potential (will galvanically corrode)
- Poor cold workability (must be hot worked or cast)



Mg Pourbaix diagram

Uses

- Aluminum Alloying 47%
- Chemical/reduction 12%
- Desulphurization 16%
- Die casting 12%
- Nodular iron 4%
- Wrought products 5%
- Other 4%

Die casting of magnesium

Liquid metal forced into a mould under pressure at a relatively high velocity and allowed to solidify with the pressure maintained

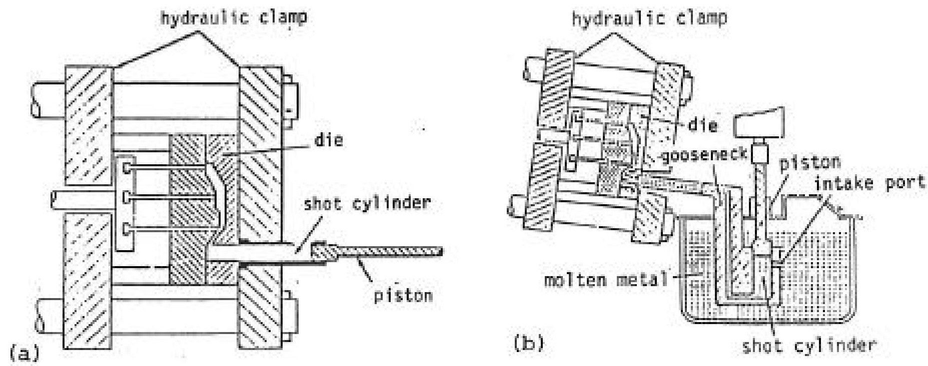


FIGURE 12-3
Schematics of (*a*) cold-chamber die casting machine and (*b*) hot-chamber die casting machine. (*After 45th Annual World Magnesium Conference, 1988, p. 38.*)

Alloys

- Major Elements: Al, Zn, Mn
- Minor Elements: Sn, Zr, Ce, Th, and Be
- Impurities: Cu, Fe, Ni

Alloy designation

- A – Al
- Z – Zn
- M – Mn
- K – Zr
- T – Sn
- Q – Ag
- C – Cu
- E – Rare Earths

Example: AZ91A

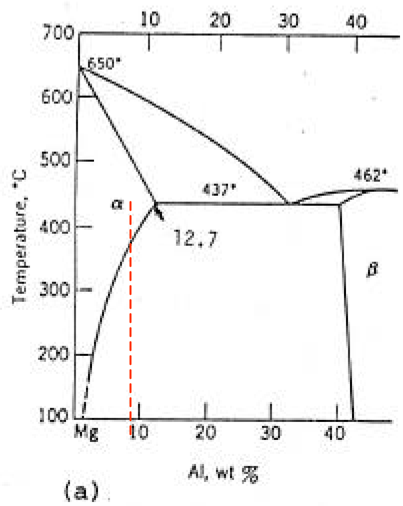
AZ	91	A
Major elements	Amounts additives	Minor

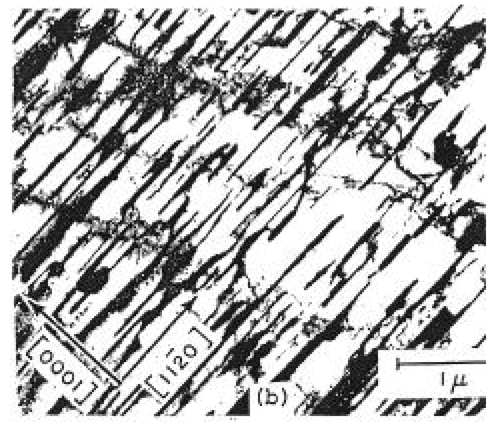
8.5-9.4 %Al
0.5-1.4 %Zn

Mg-Al Alloys

- Al up to 10% - age hardenable (increases strength, castability and corrosion resistance)
- After ppt heat treatment – an incoherent, coarse ppt produced ($Mg_{17}Al_{12}$)
- ppt not dense or fine enough to produce a strong strengthening effect
- Add Zn to improve strength

Mg-9%Al precipitation

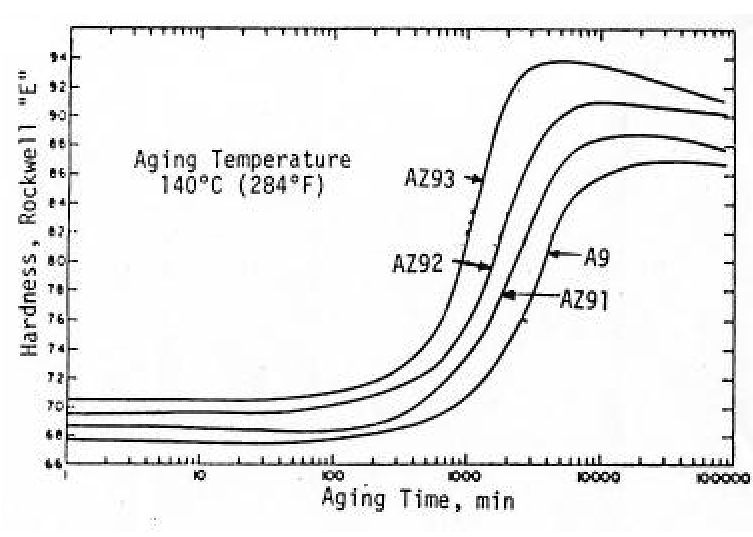




ppt formation in Mg-9 wt% Al alloy

Age hardening curves:

Mg-9% Al with 1, 2 and 3 %Zn additions



Mg-Al-Zn Alloys

- Additions of Zn improve the strength of Mg-Al alloys be refining the age-hardening ppt and solid solution strengthening
  - AZ91 – common alloy
  - AZ91D – new alloy developed in the mid 1980's (low levels of impurities,
  - Fe < 0.005%; Ni <0.001%, Cu <0.015%)
  - Dramatically increases corrosion resistance
- Rule of thumb:
  - %Al+%Zn < 10% otherwise ductility decreases dramatically due to formation of brittle intermetallic compounds

Table 12-2: Mg-Al and Mg-Al-Zn casting alloys chemical compositions and applications

Alloy	% Al	% Mn	% Zn	Other	Applications
Die castings					
AM60B	6.0	0.13*			Automobile wheels
AS41A	4.2	0.35†		1.0 Si	Automobile engines and housings; good creep resistance
AZ91D	9.0	0.15*	0.7	0.001 Ni max 0.005 Fe max	Die castings; parts for cars, lawnmowers, business machines, chain saws, hand tools, sporting goods; good corrosion resistance
Sand and permanent-mold castings					
AM100A	10.0	0.1*			Pressure-tight sand and permanent-mold castings
AZ63A	6.0	0.15*	3.0		Sand castings requiring good room-temperature strength and ductility
AZ81A	7.6	0.13*	0.7		Tough leak-proof sand castings
AZ91E	8.7	0.26†	0.7	0.001 Ni max 0.005 Fe max	Sand and permanent-mold castings requiring room-temperature strength and ductility
AZ92A	9.0	0.10*	2.0		Pressure-tight sand and permanent-mold castings; room-temperature strength and ductility

*Minimum.
†Nominal.

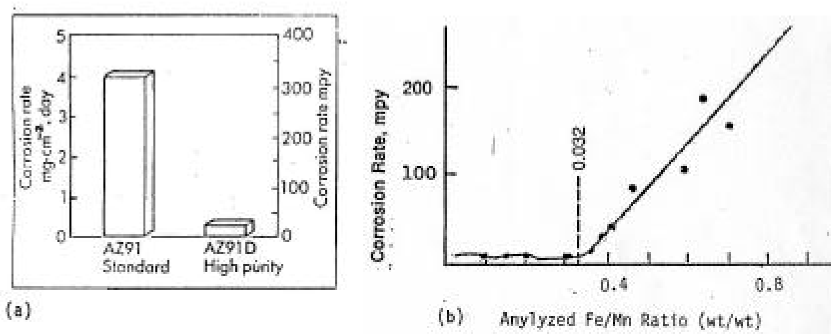
Table 12-9: Wrought Mg alloy tensile strength properties

Alloy	Temper	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elong. (%)
Sheet and plate						
AZ31B	0	32	220	15–18	103–124	2–9
	H24	29–39	200–287	14–29	96–200	6–8
Extruded bars and shapes						
AZ31B	F	31–35	213–241	16–22	110–152	4–8
AZ61B	F	32–40	220–276	16–24	110–165	7–9
AZ80A	F	42–43	289–296	27–28	186–193	4–9
ZK30A	F	40–44	276–303	28–33	193–227	8
ZK60A	F	40–43	276–296	28–31	193–213	5–6
	T5	43–46	296–317	31–38	213–262	4–6
ZM21A	F	33–35	207–241	22–23	152–158	8–20

Table 12-3: Mg-Al and Mg-Al-Zn casting alloys mechanical properties

Alloy	Tensile strength ksi	Tensile strength MPa	0.2% yield strength ksi	0.2% yield strength MPa	% elongation (in 50 mm)
Die castings					
AM60A-F	32	220	19	131	8
AS41A-F	31	214	20	138	6
AZ91D-F	34	234	23	158	3
Sand and permanent-mold castings					
AM100A-T6	35	241	17	117	2
AZ63-A-T6	34	234	16	110	3
AZ81A-T4	34	234	10	69	7
AZ91E-T6	34	234	16	110	3
AZ92A-T6	34	234	18	124	1

Fe:Mn ratio and corrosion



Note how the Fe:Mn ratio dramatically increases the corrosion rate when it is above 0.032

Advantages and Disadvantages

Advantages

- Excellent machinability
- Good castability
- Extremely light
- High thermal conductivity
- Good weldability
- Excellent strength/weight ratio
- Good creep resistance

Disadvantages

- High cost
- Poor corrosion resistance
- High electrochemical potential (will galvanically corrode)
- Poor cold workability (must be hot worked or cast)

	Metal-metal ion equilibrium (unit activity)	Electrode potential vs. normal hydrogen electrode at 25°C, volts
↑	$Au-Au^{+3}$	+1.498
	$Pt-Pt^{+2}$	+1.2
Noble or	$Pd-Pd^{+2}$	+0.987
cathodic	$Ag-Ag^{+}$	+0.799
	$Hg-Hg_2^{+2}$	+0.788
	$Cu-Cu^{+2}$	+0.337
	H_2-H^{+}	0.000
	$Pb-Pb^{+2}$	−0.126
	$Sn-Sn^{+2}$	−0.136
	$Ni-Ni^{+2}$	−0.250
	$Co-Co^{+2}$	−0.277
	$Cd-Cd^{+2}$	−0.403
	$Fe-Fe^{+2}$	−0.440
	$Cr-Cr^{+3}$	−0.744
	$Zn-Zn^{+2}$	−0.763
Active or	$Al-Al^{+3}$	−1.662
anodic	$Mg-Mg^{+2}$	−2.363
	$Na-Na^{+}$	−2.714
↓	$K-K^{+}$	−2.925

SOURCE: A. J. de Bethune and N. A. S. Loud, "Standard Aqueous Electrode Potentials and Temperature Coefficients at 25°C," Clifford A. Hampel, Skokie, Ill., 1964. See also Table 9-1.

Standard EMF series of metals

Galvanic Series

CORRODED END (Anodic)

Magnesium and its alloys

Zinc (galvanized coating on steels)

Aluminum alloy series (in order)
5xxx,3xxx,1xxx,6xxx

Cadmium

Aluminum alloy series 2xxx

HSLA and low-carbon steels, cast iron

Types 410, 304, 316 Stainless steels (active)

Lead, Tin

Copper alloys

Types 410, 304, 316 Stainless steels (passive)

Silver

Titanium

Gold

Platinum

PROTECTED END (Cathodic)

(Metals are arranged by their tendency to corrode galvanically in a seawater electrolyte)

Noble or cathodic ↑

Platinum
Gold
Graphite
Titanium
Silver
[Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
Hastelloy C (62 Ni, 17 Cr, 15 Mo)]
[18-8 Mo stainless steel (passive)
18-8 stainless steel (passive)
Chromium stainless steel 11-30% Cr (passive)]
[Inconel (passive) (80 Ni, 13 Cr, 7 Fe)
Nickel (passive)]
Silver solder
[Monel (70 Ni, 30 Cu)
Cupronickels (60-90 Cu, 40-10 Ni)
Bronzes (Cu-Sn)
Copper
Brasses (Cu-Zn)]
[Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)]
[Inconel (active)
Nickel (active)]
Tin
Lead
Lead-tin solders
[18-8 Mo stainless steel (active)
18-8 stainless steel (active)]
Ni-Resist (high Ni cast iron)
Chromium stainless steel, 13% Cr (active)
[Cast iron
Steel or iron]
2024 aluminum (4.5 Cu, 1.5 Mg, 0.6 Mn)
Cadmium
Commercially pure aluminum (1100)
Zinc
Magnesium and magnesium alloys

Active or anodic ↓

Galvanic series of some commercial metals and alloys in seawater

High temperature Mg casting alloys

- Can be used up to temperatures of ~250°C
- Rare earth elements added to improve creep resistance (they form ppt's at the grain boundaries and hold them in place)
- Mg + Zr + Rare Earths

Grain refiner (Zr)

Creep resistance (Rare Earths)

High temperature Mg casting alloys

Table 12-6: Chemical compositions & applications

Alloy	% Ag	% Y	% Re	% Cu	% Zr	Applications
QE22A	2.5		2.2		0.7	Sand and permanent-mold castings for elevated temperature use to 200°C; aero-engine components; helicopter housings; missiles; racing car parts
EQ21	1.5		2.1	0.08	0.6	
WE43		4.0	3.4		0.4 (min)	Sand and permanent-mold castings for elevated temperature use to 250°C; good corrosion resistance; aero-engine components; helicopter housings

Table 12-7: Mechanical properties at RT

Alloy	Temper	Tensile strength		0.2% yield strength		% elongation in 50 mm
		ksi	MPa	ksi	MPa	
QE22A	T6	35	241	25	172	2
EQ21	T6	34	234	25	172	2
WE43	T6	36	250	23	160	2

Mg-Zn-Zr and Mg-Zn-rare earth-Zr alloys

Table 12-4: Chemical compositions & applications

Alloy	% Zn	% RE	% Zr	Applications
ZK51A	4.6		0.7	Sand castings; good strength at room temperature
ZK61A	6.0		0.8	Sand castings; good strength at room temperature
EZ33A	2.6	3.2	0.7	Pressure-tight sand and permanent-mold castings for applications at 175–260°C
ZE41A	4.2		0.7	Sand castings; good strength at room temperature; improved castability over ZK alloys
ZE63A	5.7	2.5	0.7	

Table 12-5: Mechanical properties at RT

Alloy	Temper	Tensile strength		0.2% yield strength		% elongation in 50 mm
		ksi	MPa	ksi	MPa	
ZK51A	T5	34	234	20	138	5
ZK61A	T6	40	275	26	179	5
EZ33A	T5	20	138	14	96	2
ZE41A	T5	29	200	19.5	134	2–5
ZE63A	T6	40	275	27	186	5