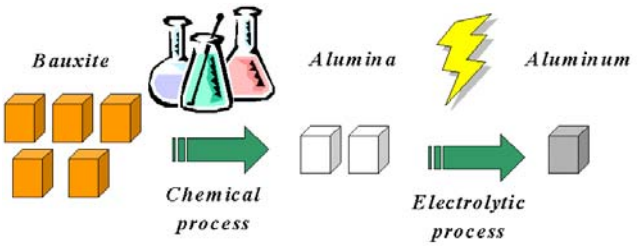
Lecture 16:
Light Metals – Non-heat treatable aluminum alloys

MMat 380

Topics

- Aluminum – Chapter 5 Smith (176-229)
- Magnesium – Chapter 12 Smith (537-560)
- Titanium – Chapter 10 Smith (433-484)



Extraction of Aluminum

General characteristics

Property	Al	Mg	Ti	Cu	Fe
E (GPa)	70	45	120	130	212
M.P. (°C)	660	650	1668	1083	1536
Density (gms/cm^3)	2.70	1.74	4.51	8.96	7.86
Resistivity (μΩ-cm)	2.8	4.6	3.2	1.7	10.0
Specific resistivity (μΩ gms /cm^2)	7.7	8.0	14.5	15.5	78.6

N.B. Resistivity = property of a material which resists the flow of electrical current

General characteristics

Property	Aluminum alloys			Cu	Mild Steel	Stainless Steel	Mg
	1100	5454	6061				
Density (g/m^3)	2.81	2.78	2.81	8.96	7.83	7.91	1.74
Electrical Conductivity (%IACS)	59	34	43	100	10	2	38
Coeff. Linear Expansion (10^{-6} mm/mm/^{o}C)	23.5	23.5	23.5	16.5	12.6	16.2	25.8




Cost comparison

Metal	Price (US$/tonne)	Price relative to carbon steel
Carbon steel	225	1
Aluminum	1000	4
Stainless steel	650	3
Copper	2300	10
Zinc	998	4
Nickel	6200	28
Magnesium	2600	12
Tin	5400	25
Titanium	6612	30

Aluminum industry

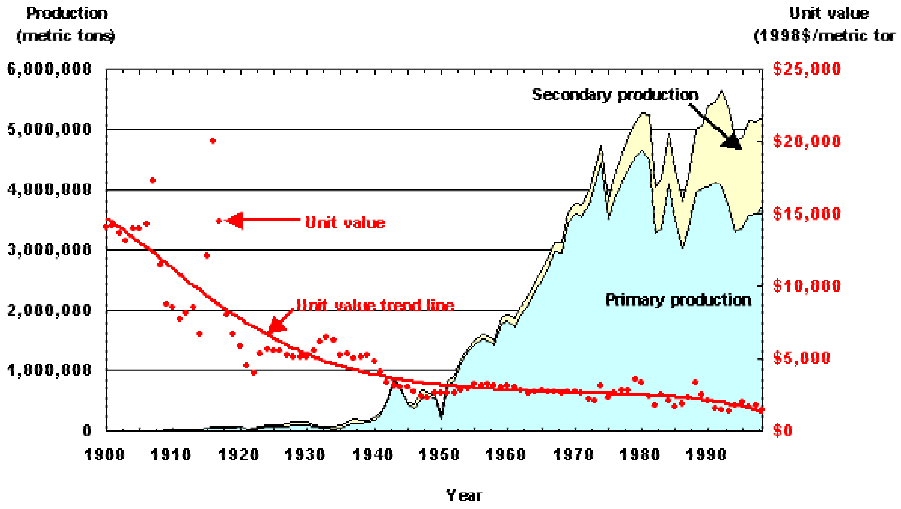
Primary aluminum industry

- Principle resources:
  - Bauxite
  - Alunite
  - Clays
  - Nepheline
  - Other
- Mine
- Alumina refinery
- Aluminum smelter
- Fabrication industry

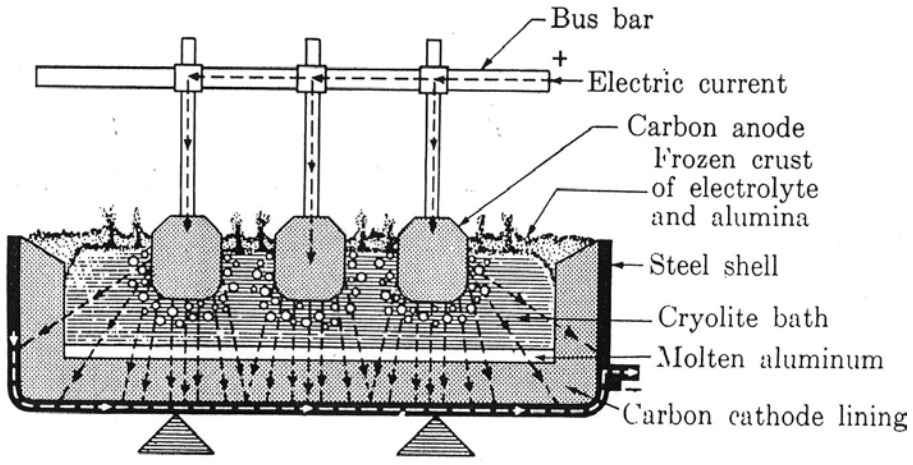
Aluminum recycling industry

- Principal resources:
  - Old scrap (used cans, automobile parts, etc.)
  - New scrap (production and fabrication waste)
- Scrap industry
  - Used beverage can industry
  - Manufacturing industry
- Secondary smelter
- Fabrication industry

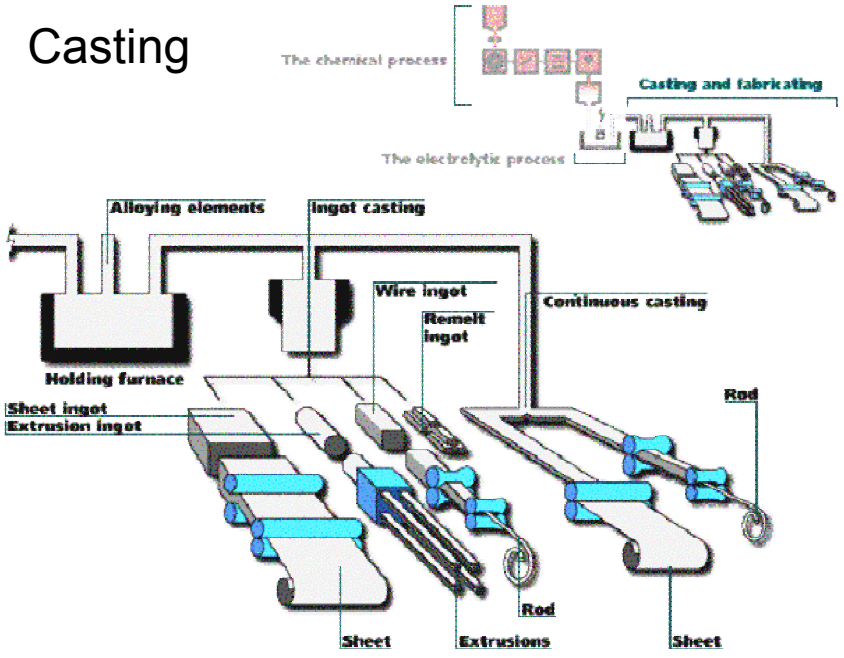
US primary and secondary Al production and primary Al unit value 1900-1998



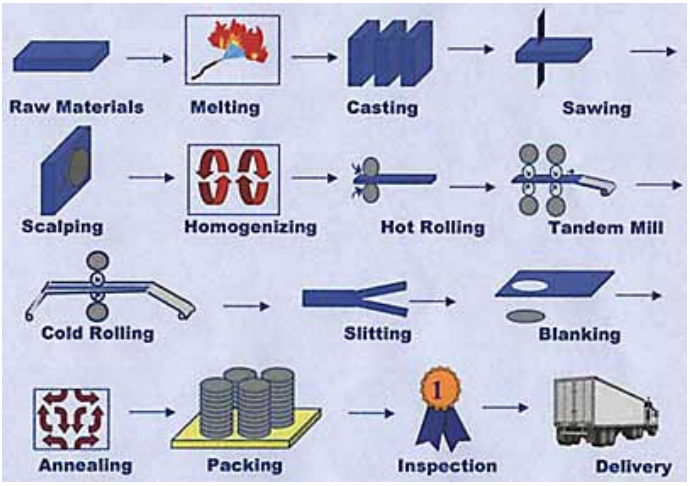
Electrolytic cell used to produce Al (Hall-Heroult Process)



Casting



Aluminum fabrication



Aluminum alloys

- Melting point 660°C – softens at 150-200°C
- FCC crystal structure – no phase transformation
- No ductile-to-brittle transition
- Density = 2.7 gm/cm^3 (vs. 7.7 gm/cm^3 for Fe)
- E = 70 GPa (vs. 210 GPa for Fe)
- Cost in sheet form: ~4.5 x mild steel
  (~1.5 x for equal thickness)
- Pure Al Y.S. ~35 MPa (alloys up to 560 MPa)

Aluminum alloys

- Low strength alloys (up to 275 MPa) easily welded
- Corrosion resistance – good to fair depending on alloy (Al_2O_3)
- High electrical conductivity (62% IASC*)
- Easily formed by extrusion, forging rolling etc (foil), can be formed at low temperatures and intricate shapes (FCC crystal structure)

*International Annealed Standard for Copper

Constitution of alloys

- Major alloying elements: Cu, Mg, Mn, Si, Zn
- Classification of wrought alloys
  - 2 groups – Heat treatables, non-heat treatables
  - 4 digits – 1st digit indicates alloy group

In 1xxx last two digits indicate min Al% (.xx)

In 2xxx-8xxx last two digits id. Alloy in series as commercially available, 2nd digit indicates alloy modifications

0 original alloy

1-9 modifications

Constitution of Alloys

	non-heat treatables	heat treatables
Al>99.0%	1xxx (foil)	
Copper		2xxx+Mg+Mn (aircraft)
Manganese	3xxx +Si	
Magnesium	5xxx +Mn+Cr	
Mg+Si		6xxx+Cu+Si+Cr+Mn
Zinc		7xxx+Mg
Other elements		8xxx (Li-aircraft)

Cast aluminum alloys

Developed for fluidity and feeding ability

- 1xx.x (pure Al)
- 2xx.x (Cu)
- 3xx.x (Si w/ Cu/Mg)
- 4xx.x (Si)
- 5xx.x (Mg)
- 7xx.x (Zn)
- 8xx.x (Sn)
- 9xx.x (other element)

First digit: alloy group
next 2 digits: alloy or purity
Last digit: product form: casting/ingot

Aluminum alloys

- Strengthening mechanisms
  - solid solution hardening
  - cold work (strain hardening)
  - age hardening

$$\sigma_{ys} = \sigma_o + kd^{-1/2}$$

- Age hardening
  - type of phase diagram and aging behaviour
- Alloy designation (previous slide)
- Temper designation
  - O, F, $H_{1x\ (x=2,4,6,8)}$, T3, T4, T6, T8

Fully annealed

Aluminum Alloys

- Methods of joining
  - 1xxx, 3xxx, 5xxx can be welded
  - 2xxx, 7xxx **most** are non-weldable (must be riveted, bolted etc.)
  - 6xxx can be welded
  - **Some** 2xxx and 7xxx can be welded (i.e., 2219 and 7005)
- Highest strength
  - Heat treatables 7xxx series (600 MPa)
  - Non heat treatables 5xxx series (275 MPa)

Basic Temper designations

F: As fabricated. No control over amount of strain hardening; no mechanical property limits

O: Annealed and recrystallized. Temper with the lowest strength and highest ductility

H : Strain-hardened, subdivided.

T: Heat treated to produce stable tempers other than F or O, subdivided

Strain hardened subdivisions

H1: strain-hardened only

degree indicated by second digit and varies from ¼-hard (H12) to full-hard (H18) which is produced with approx. 75% reduction in area

H2: strain-hardened and partially annealed

Tempers ranging from ¼-hard to full hard obtained by partial annealing of cold-worked materials with strengths initially > desired. (H22, H24, H26 and H28)

H3: strain hardened and stabilised

Tempers for age-softening Al-Mg alloys that are strain-hardened and then heated at low T to increase ductility and stabilise mechanical properties. (H32, H34, H36, and H38)

Heat-treated subdivisions

T1: Naturally aged (product is cooled from an elevated-T shaping process and naturally aged to a substantially stable condition)

T3: Solution heat-treated, cold-worked and naturally aged to a substantially stable condition

T4: Solution heat-treated and naturally aged to a substantially stable condition.

T5: Cooled from an elevated-T shaping process and then artificially aged

★ T6: Solution heat-treated and then artificially aged

Above R.T.

T7: Solution heat-treated and stabilized

T8: Solution heat-treated, cold-worked, and then artificially aged.

Aluminum Alloys

- Corrosion resistance – Al most corrosion resistant in the pure form
  - 1xxx, 3xxx and 5xxx series best
  - 2xxx and 7xxx series usually clad with pure Al
- Electrical conductivity
  - Depends on alloy content (dissolved) and strain in lattice
- Anodizing – Deliberate Al_2O_3 layer on surface for corrosion protection

Strengthening mechanisms in aluminum alloys

- Age hardening
  - (Heat treatables)
- Solution hardening
  - (Heat treatables, non heat treatables)
- Cold working (strain hardening)
  - (Heat treatables, non heat treatables)

Major effects of alloy additions

- Cu: High strength from age hardening, not weldable (AA2xxx)
- Mn: Solution hardening (AA3xxx)
- Mn+Mg: Solution hardening even better
- Mg: Solution hardening – best corrosion resistance next to pure Al (AA5xxx)
- Mg+Si: Moderately heat treatable and corrosion resistance and weldability – good medium alloy (AA6xxx)
- Zn+Mg: High strength, not weldable (AA7xxx)
- Alclad
  - High purity Al skin for corrosion resistance
  - May protect galvanically

Mechanical properties

Non Heat Treatables		
Alloy	**Y.S. (max)**	**Applications**
1xxx	97	1100 – foil, fin stock
3xxx	160	3104 – canstock
5xxx	180	5052 – transportation
Heat Treatables		
2xxx	402-435	2024 – aircraft
7xxx	270-300	6061 – ladders, bikes
6xxx	450-590	7075 – aircraft

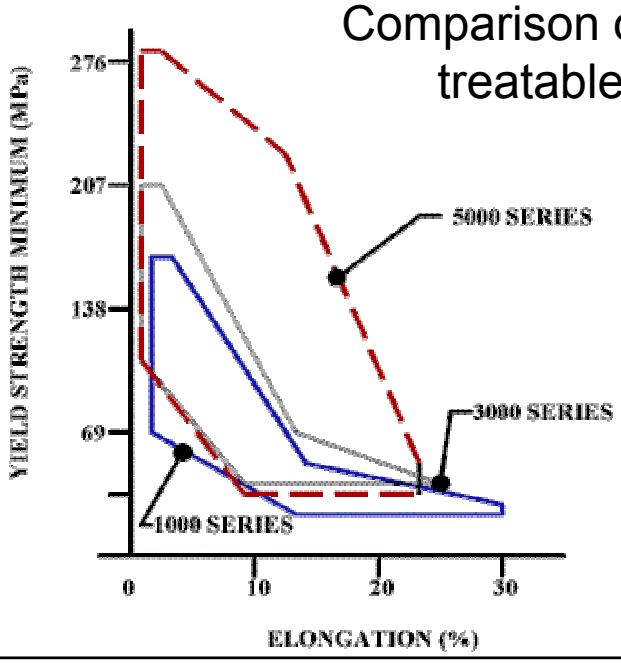
Typical mechanical properties and applications

Alloy number*	Chemical composition, wt %†	Condition‡	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation, %	Typical applications
			Wrought alloys					
1100	99.0 min Al, 0.12 Cu	Annealed (-O)	13	89 (av)	3.5	24 (av)	25	Sheet metal work, fin stock
		Half-hard (-H14)	18	124 (av)	14	97 (av)	4	
3003	1.2 Mn	Annealed (-O)	17	117 (av)	5	34 (av)	23	Pressure vessels, chemical equipment, sheet metal work
		Half-hard (-H14)	23	159 (av)	23	159 (av)	17	
5052	2.5 Mg, 0.25 Cr	Annealed (-O)	28	193 (av)	9.5	65 (av)	18	Bus, truck, and marine uses, hydraulic tubes
		Half-hard (-H34)	38	262 (av)	26	179 (av)	4	
2024	4.4 Cu, 1.5 Mg, 0.6 Mn	Annealed (-O)	32	220 (max)	14	97 (max)	12	Aircraft structures
		Heat-treated (-T6)	64	442 (min)	50	345 (min)	5	
6061	1.0 Mg, 0.6 Si, 0.27 Cu, 0.2 Cr	Annealed (-O)	22	152 (max)	12	82 (max)	16	Truck and marine structures, pipelines, railings
		Heat-treated (-T6)	42	290 (min)	35	241 (min)	10	
7075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Annealed (-O)	40	276 (max)	21	145 (max)	10	Aircraft and other structures
		Heat-treated (-T6)	73	504 (min)	62	428 (min)	8	

Mechanical properties of CP aluminum

Alloy	Temper	Tensile strength, psi	Tensile yield strength,* psi	Elongation, % in 2 in	Hardness,† Bhn	Shear strength, psi	Fatigue limit,‡ psi
1199	O	6,500	1,500	50			
	H18	17,000	16,000	5			
1180	O	9,000	3,000	45			
	H18	18,000	17,000	5			
1060	O	10,000	4,000	43	19	7,000	3000
	H14	14,000	13,000	12	26	9,000	5000
	H18	19,000	18,000	6	35	11,000	6500
EC	O	12,000	4,000	23§		8,000	
	H14	16,000	14,000			10,000	
	H19	27,000	24,000	2.5§		15,000	
1145	O	11,000	5,000	40		8,000	
	H18	21,000	17,000	5		12,000	
1100	O	13,000	5,000	35	23	9,000	5000
	H14	18,000	17,000	9	32	11,000	7000
	H18	24,000	22,000	5	44	13,000	9000

Comparison of non-heat treatable alloys



Effect of Mg content on properties of Al

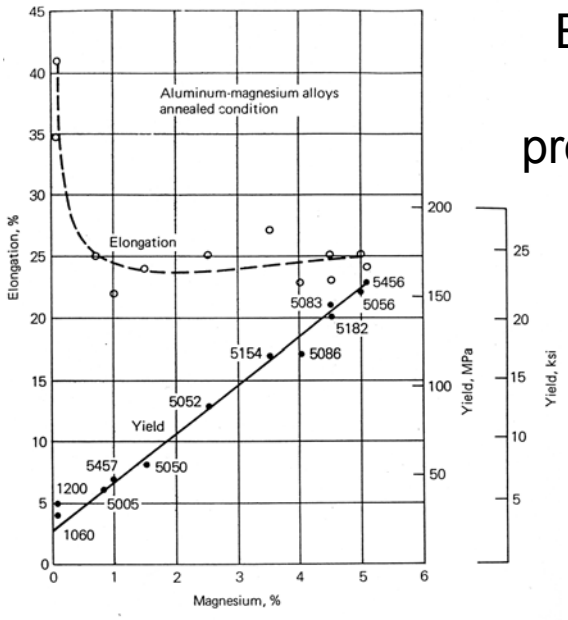


Fig. 9. Correlation between tensile yield, elongation, and magnesium content for some commercial alloys. (Ref 14)

Non-heat treatable alloys

5xxx

- For welded structures – can't use cold worked "H" strengths
- Max. annealed strengths 134-170 MPa
- Therefore max. design strength for welded structures i.e., fishboats etc.
- Best corrosion resistance and strength of all the alloys

Applications of Al-Mg alloys

Alloy	% Composition	Applications
5005	0.8 Mg	Appliances; utensils; architectural trim; electrical conductors
5050	1.4 Mg	Builders' hardware; refrigerator trim; coiled tubes
5052	2.5 Mg, 0.25 Cr	Sheet metal work; hydraulic tubes; appliances; bus, truck and marine uses
5056	0.12 Mn, 5.1 Mg, 0.12 Cr	Cable sheathing; rivets for magnesium; screen wire; zippers
5083	0.7 Mn, 4.45 Mg, 0.15 Cr	Unfired, welded pressure vessels; marine, auto, and aircraft parts; cryogenics; TV towers; drilling rigs; transportation equipment; missile components; armor plate
5086	0.45 Mn, 4.0 Mg, 0.15Cr	
5154	3.5 Mg, 0.25 Cr	Welded structures; storage tanks; pressure vessels; salt-water service
5252	2.5 Mg	Auto and appliance trim
5254	3.5 Mg, 0.25 Cr	Hydrogen peroxide and chemical storage vessels
5356	0.12 Mn, 5.0 Mg, 0.12 Cr	Welding rod, wire, and electrodes
5454	0.8 Mn, 2.7 Mg, 0.12 Cr	Welding structures; pressure vessels; marine service; tubing
5456	0.8 Mn, 5.1 Mg, 0.12 Cr	High-strength welded structures; storage tanks; pressure vessels; marine service
5457	0.3 Mn, 1.0 Mg	Anodized auto and appliance trim (good formability in annealed temper)
5652	2.5 Mg, 0.25 Cr	Hydrogen peroxide and chemical storage vessels
5657	0.8 Mg	Anodized auto and appliance trim (good brightness)