Wrought Aluminum I - Metallurgy

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Course learning objectives

ð Explain the composition and strength differences between the alloy families.

ð Explain the methods for modifying aluminum alloy strength.

ð Describe the metallurgical changes that occur inside metals during cold-working, annealing, and precipitation strengthening heat treatment.

ð Relate composition and microstructure to aluminum alloy strength.

ð Explain the aluminum temper designations for cold-worked and precipitation strengthened alloys.

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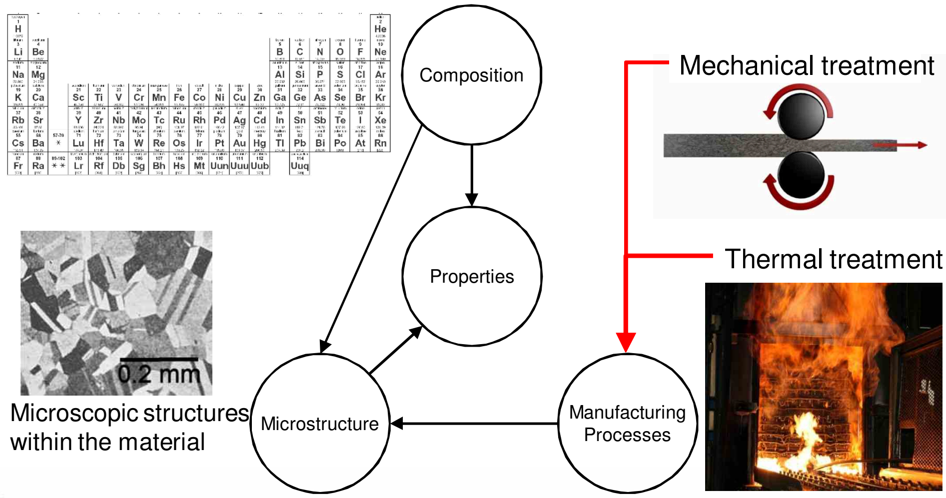
Metal properties



Wrought Aluminum Alloy Series

Different alloying elements enables different properties to be obtained

Strength values are typical strengths

Alloy series	Alloying elements	Yield Strength ksi (MPa)	Tensile Strength ksi (MPa)
1xxx	None	4-24 (30-165)	10-27 (70-185)
2xxx	Primary: Cu Secondary: Mg	27-66 (185-455)	43-72 (295-495)
3xxx	Primary: Mn Secondary: Mg	6-36 (40-250)	16-41 (110-285)
4xxx	Primary: Si	46 (315) 4032	55 (380) 4032
5xxx	Primary: Mg Secondary: Mn	6-50 (40-345)	18-60 (125-415)
6xxx	Primary: Mg, Si	13-55 (90-380)	22-58 (150-400)
7xxx	Primary: Zn Secondary: Mg, Cu	61-78 (420-540)	71-88 (490-605)
8xxx	Primary: other than listed above		

Aluminum strengthening mechanisms

Cold working (strain hardening)

Solid solution

Precipitation

Dispersion

Alloy strengthening mechanisms

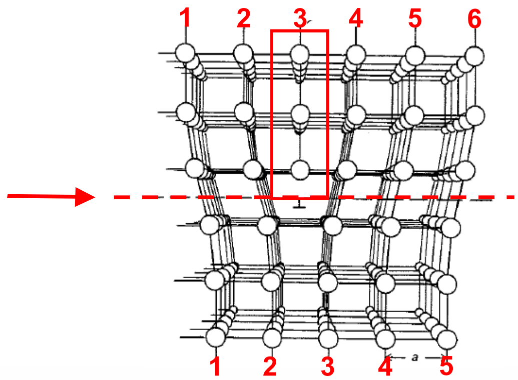
Alloy series	Alloying elements	Yield Strength ksi (MPa)	Tensile Strength ksi (MPa)	Primary strengthening mechanisms
1xxx	None	4¯24 (30-165)	10-27 (70-185)	Strain hardening
2xxx	Primary: Cu Secondary: Mg	27¯66 (185-455)	43-72 (295-495)	Precipitation, strain hardening
3xxx	Primary: Mn Secondary: Mg	6-36 (40-250)	16-41 (110-285)	Dispersion, strain hardening, solid solution
4xxx	Primary: Si	46 (315) 4032	55 (380) 4032	Strain hardening (4032: Precipitation)
5xxx	Primary: Mg Secondary: Mn	6-50 (40-345)	18-60 (125-415)	Solid solution, strain hardening
6xxx	Primary: Mg, Si	13-55 (90-380)	22-58 (150-400)	Precipitation, strain hardening
7xxx	Primary: Zn Secondary: Mg, Cu	61-78 (420-540)	71-88 (490-605)	Precipitation, strain hardening

Dislocation

Extra plane of atoms inserted between two other planes of atoms

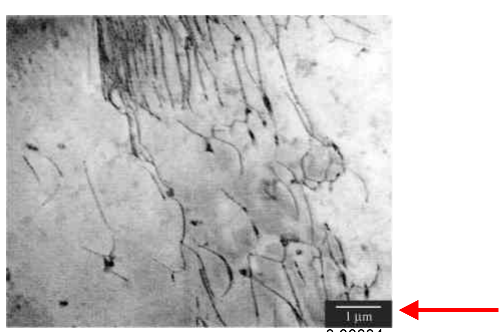
Present in all metals

- ð About 10 million dislocations/cm^2 in as-cast metals



A.G. Guy, The Essentials of Materials Science, McGraw-Hill, 1976.
(Courtesy of Irene Guy)

Electron microscope micrograph of dislocations in a metal



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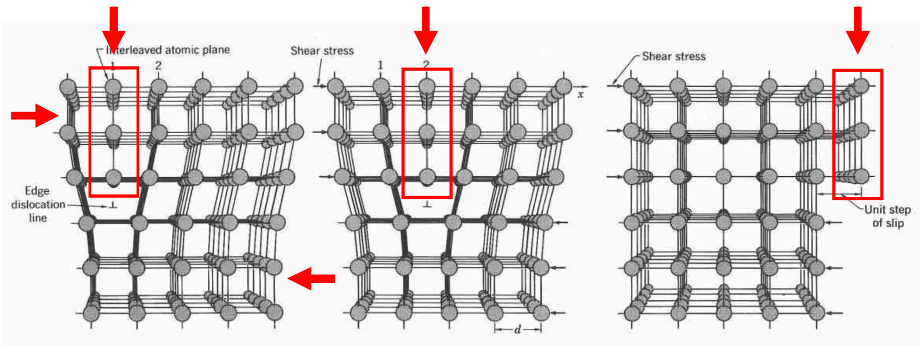
Dislocations move when stress exceeds a certain level

- Yield stress
- Metal undergoes permanent deformation



A.G. Guy, The Essentials of Materials Science, McGraw-Hill, 1976. (Courtesy of Irene Guy)

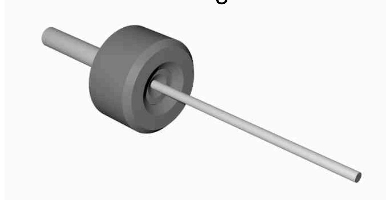
Cold working (Strain hardening)

Plastic deformation of a metal at low temperatures

- Less than about one-third melting point temperature

Cold rolling

Wire drawing



Most of the energy expended in cold work appears in the form of heat

Portion of the energy goes into creation of more dislocations

ð Dislocations generate new dislocations

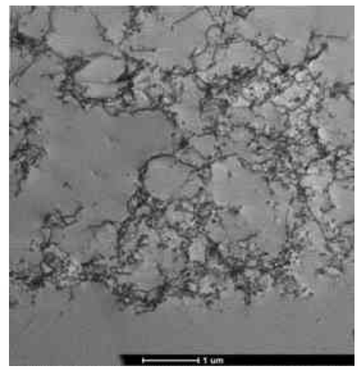
ð Soft, annealed metal: 10^6 to 10^8 dislocations/cm^2

ð Heavily cold worked metal: 10^{12} dislocations/cm^2

Addition dislocations created interfere with each other

ð Increased stress to move dislocations

ð Increase in metal strength and hardness



<u>Aluminum strain hardened tempers</u>

H1x, Strain-hardened only

H2x, Strain-hardened and partially annealed

H3x, Strain-hardened and stabilized

X indicates amount an alloy has been strain hardened

H1x, H2x, H3x

Digit following H1, H2, and H3 indicates degree of strain hardening

- ð 1 through 9
- ð Indicates progressively greater strain hardening

x	Tensile strength
9	Exceeds 8 by at least 10 MPa (2 ksi)
8	Equivalent to that achieved by about 75% cold reduction following full annealing
7	Approximately midway between 6 and 8
6	Midway between 4 and 8 tempers
5	Approximately midway between 4 and 6 temper
4	Approximately midway between fully annealed and the 8 temper
3	Approximately midway between 2 and 4 tempers
2	Midway between fully annealed and the 4 temper
1	Approximately midway between fully annealed and 2 temper

H1x, Strain-Hardened

O = fully annealed (metal at lowest strength)

	1100 Aluminum			3003 Aluminum		
Temper	Tensile strength (ksi)	Yield strength (ksi)	Elongation (%)	Tensile strength (ksi)	Yield strength (ksi)	Elongation (%)
O	13	5	40	16	6	40
H14	18	17	20	22	21	16
H18	24	22	15	29	27	10

O temper - Fully annealed

Lowest strength, highest ductility condition

Heat to at least 650 °F to eliminate strengthening effects of cold working

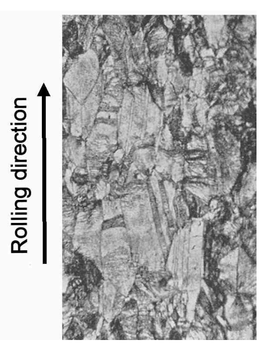
Metallurgical changes occur inside the metal

1. Eliminate dislocations and crystal lattice damage from cold working
2. New grains form and grow

New grains have much fewer number of dislocations compared to cold-worked metal

ð Changes during annealing involve the motion of atoms through the metal

Brass cold-rolled and annealed



A
50% reduction
80 ksi yield strength

B
50% reduction
1022 °F (550 °C) anneal
11 ksi yield strength

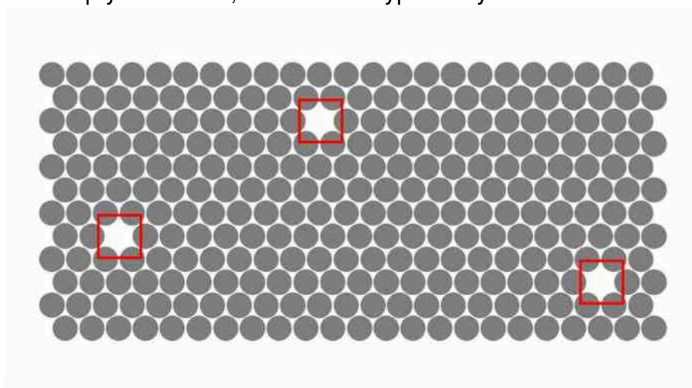
C
50% reduction
1202 °F (650 °C) anneal
9 ksi yield strength

Diffusion

Atoms can move if they have enough energy

Involves atoms jumping from one lattice site to an adjacent lattice site

Vacancy is an empty lattice site, and another type of crystal defect



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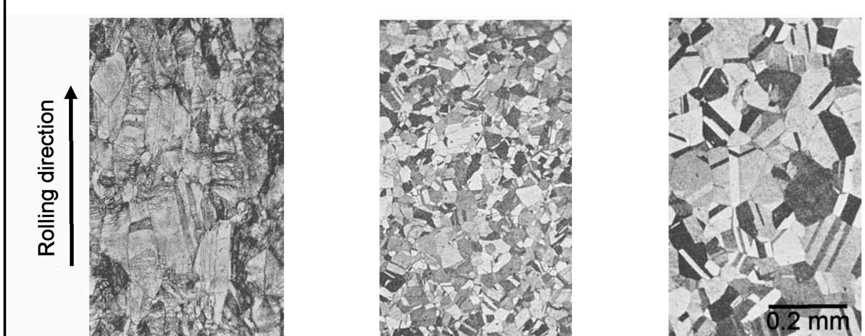
Annealing and diffusion

Higher annealing temperature



A
50% reduction
80 ksi yield strength

B
50% reduction
1022 °F (550 °C) anneal
11 ksi yield strength

C
50% reduction
1202 °F (650 °C) anneal
9 ksi yield strength

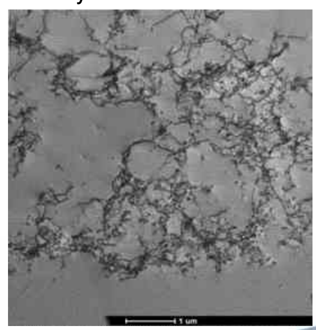
H2x, Strain-Hardened and Partially Annealed

1. Cold-work more than desired final temper
2. Reduce strength to desired level by partial annealing

Partial anneal at a lower temperature than full anneal

ð About 350 to 400 °F
ð Change in arrangement of dislocations
ð However, number of dislocations present prior to anneal are about the same
ð Result is strength similar to H1 temper, but with better ductility

Dislocations in a metal

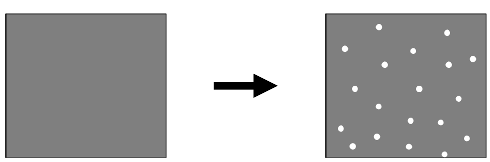


Stabilization heat treatment

Formation of particles involves diffusion

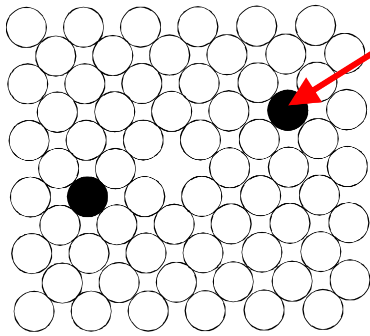
After cold working, heat treat at 250 to 350 °F

ð Quickly form Mg_2Al_3 particles
ð Obtain microstructure that will be stable at room temperature
ð Strength will not decrease further at room temperature



Solid solution strengthening

Increase in metal strength due to presence of substitution atoms



Substitution (solute)

ð Atom of alloying or impurity element that occupies lattice site of main metal

ð Examples of substitutions in Al include Mn, Mg, Fe, Si, and Cu

ð Substitution atom `dissolved_ in crystal lattice → mixture of atoms

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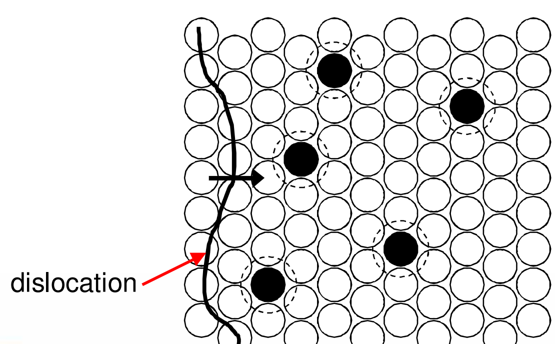
Substitutions atoms are obstacles to dislocations

Increased stress required to move dislocations past substitution atoms

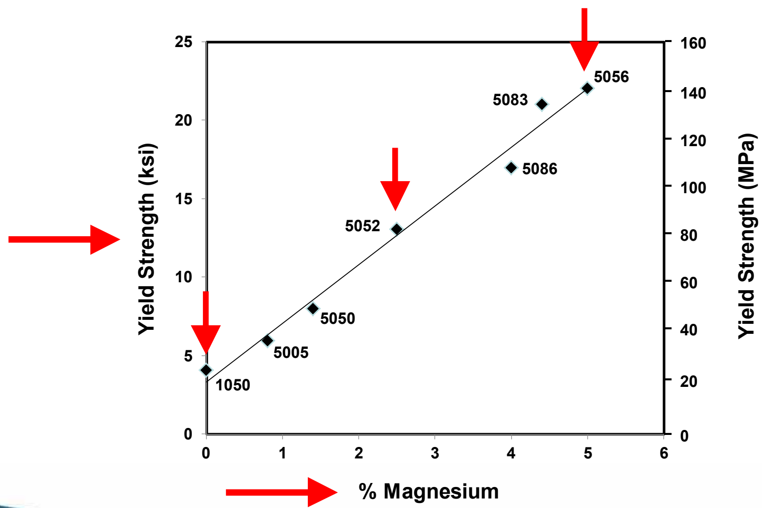
Stress to move dislocations increases as number of substitution atoms increases

Not every alloying element has the same strengthening effects

ð Some elements have greater strengthening effects than other elements.



Effect of magnesium content on strength of annealed aluminum



Precipitation Strengthening

Also referred to as age hardening

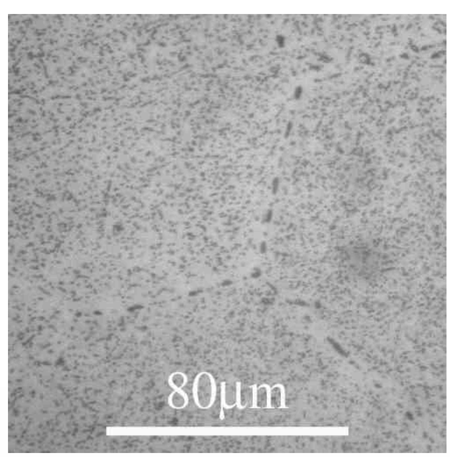
Particles form within aluminum

ð Particles referred to as precipitates

ð Compounds of elements in alloy

ð < 0.001 mm diameter

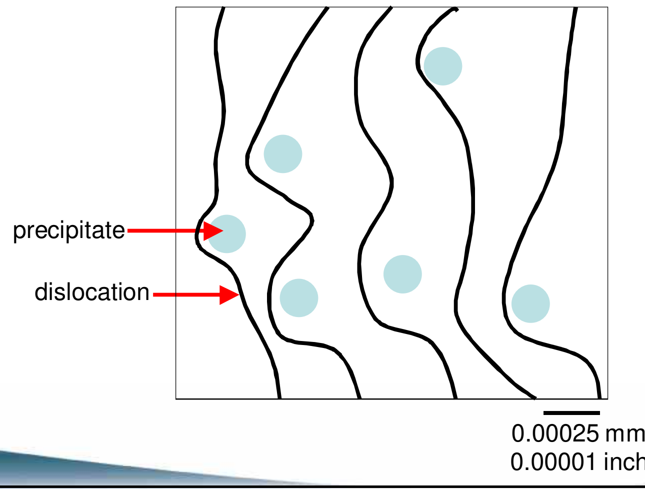
Al_2Cu precipitates in Al-Cu alloy



Precipitates are obstacles to dislocation motion

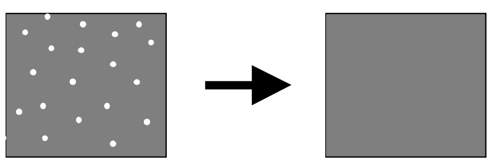
Greater stress required to move dislocations through metal

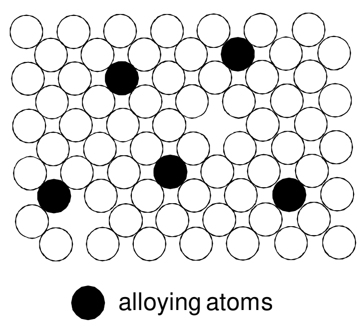
Strength and hardness increases



Precipitation heat treating process

1) Solution heat treat: Dissolve precipitates and form solid solution





2xxx: 920 - 995 °F
6xxx: 945 - 1115 °F
7xxx: 870 - 900 °F

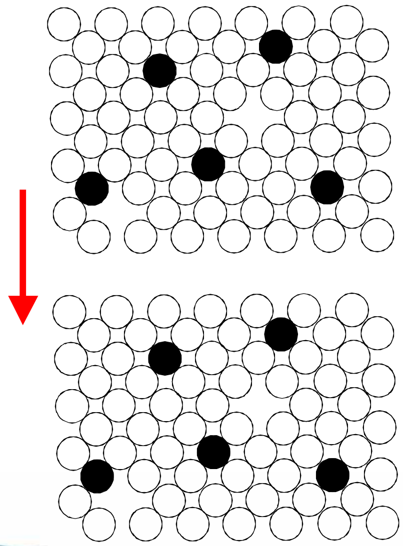
During elevated temperature shaping processes such as extrusion, the alloy may get hot enough that the solution treatment is accomplished during shaping

Precipitation heat treating process

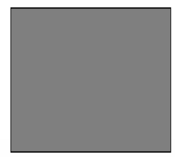
1) Solution heat treat

2) Fast cool

78 °F (25 °C)



Microstructure



Precipitation heat treating process

3) Aging treatment

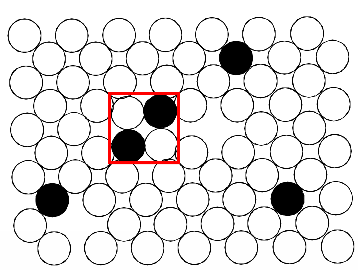
ð Precipitates form

ð Room temperature (natural aging) or elevated temperature (artificial aging)

ð Alloying atoms form precipitates with aluminum or other alloying atoms

ð Number of precipitates depends on aging temperature

ð Metal strength increases as number of precipitates increases



Microstructure after aging