Chapter 11: Applications and Processing of Metal Alloys

ISSUES TO ADDRESS...

- How are metal alloys classified and what are their common applications?
- What are some of the common fabrication techniques for metals?
- What heat treatment procedures are used to improve the mechanical properties of both ferrous and nonferrous alloys?

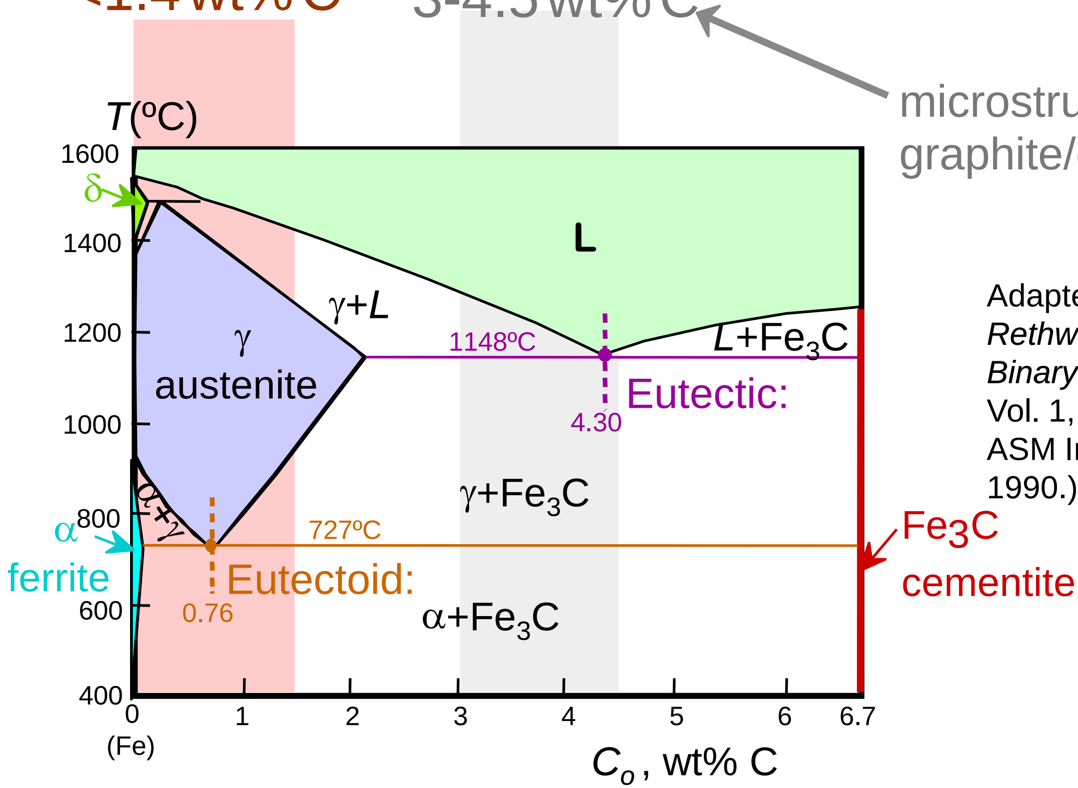
Classification of Metal Alloys

Metal Alloys

- Ferrous
  - Steels <1.4 wt% C
  - Cast Irons 3-4.5 wt% C
- Nonferrous

Adapted from Fig. 11.1, *Callister & Rethwisch 8e.*

microstructure: ferrite, graphite/cementite



Adapted from Fig. 9.24, *Callister & Rethwisch 8e.* (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)

Steels

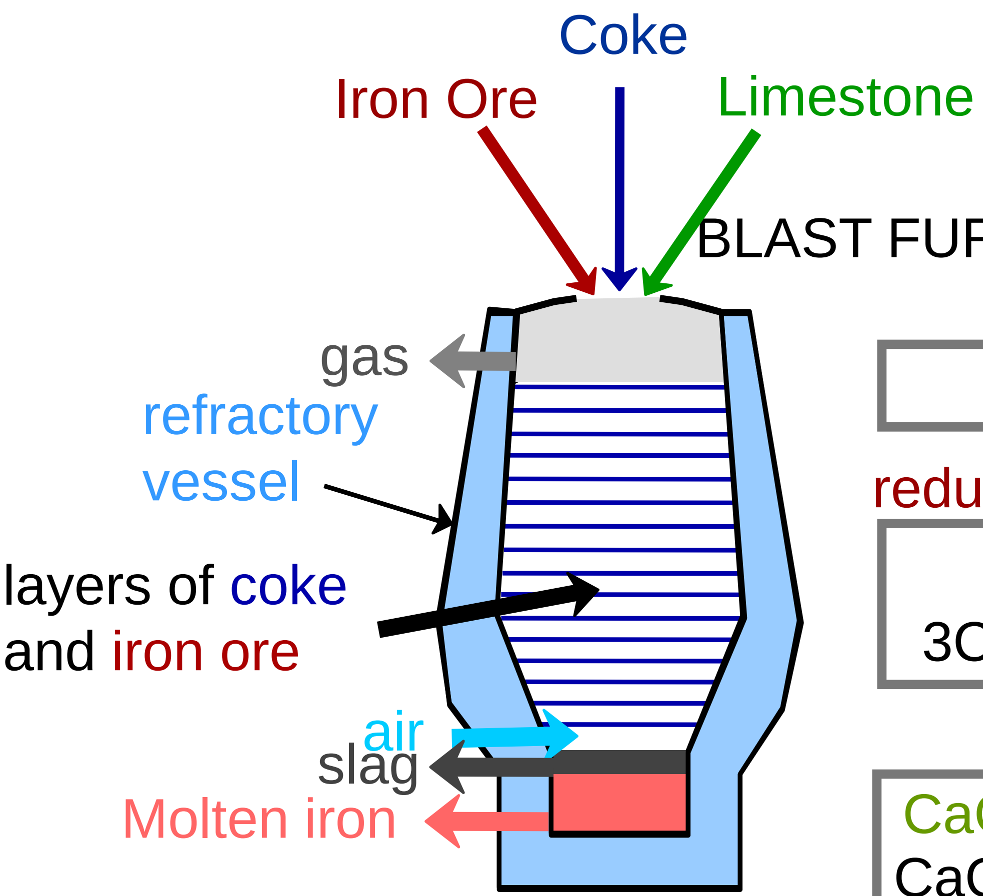
- **Low Alloy**
  - low carbon <0.25 wt% C: plain, HSLA
  - Med carbon 0.25-0.6 wt% C: plain, heat treatable
  - high carbon 0.6-1.4 wt% C: plain, tool
- **High Alloy**: stainless

Name	plain	HSLA	plain	heat treatable	plain	tool	stainless
Additions	none	Cr,V Ni, Mo	none	Cr, Ni Mo	none	Cr, V, Mo, W	Cr, Ni, Mo
Example	1010	4310	1040	4340	1095	4190	304, 409
Hardenability	0	+	+	++	++	+++	varies
TS	-	0	+	++	+	++	varies
EL	+	+	0	-	-	--	++
Uses	auto struc. sheet	bridges towers press. vessels	crank shafts bolts hammers blades	pistons gears wear applic.	wear applic.	drills saws dies	high T applic. turbines furnaces Very corros. resistant

increasing strength, cost, decreasing ductility →

Based on data provided in Tables 11.1(b), 11.2(b), 11.3, and 11.4, *Callister & Rethwisch 8e.*

Refinement of Steel from Ore



heat generation

$$C + O_2 \rightarrow CO_2$$

reduction of iron ore to metal

$$CO_2 + C \rightarrow 2CO$$

$$3CO + Fe_2O_3 \rightarrow 2Fe + 3CO_2$$

purification

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaO + SiO_2 + Al_2O_3 \rightarrow \text{slag}$$

Ferrous Alloys

Iron-based alloys

- Steels
- Cast Irons

Nomenclature for steels (AISI/SAE)

10xx Plain Carbon Steels

11xx Plain Carbon Steels (resulfurized for machinability)

15xx Mn (1.00 - 1.65%)

40xx Mo (0.20 ~ 0.30%)

43xx Ni (1.65 - 2.00%), Cr (0.40 - 0.90%), Mo (0.20 - 0.30%)

44xx Mo (0.5%)

where xx is wt% C x 100

example: 1060 steel – plain carbon steel with 0.60 wt% C

Stainless Steel >11% Cr

Cast Irons

- Ferrous alloys with > 2.1 wt% C
  - more commonly 3 - 4.5 wt% C
- Low melting – relatively easy to cast
- Generally brittle

- Cementite decomposes to ferrite + graphite

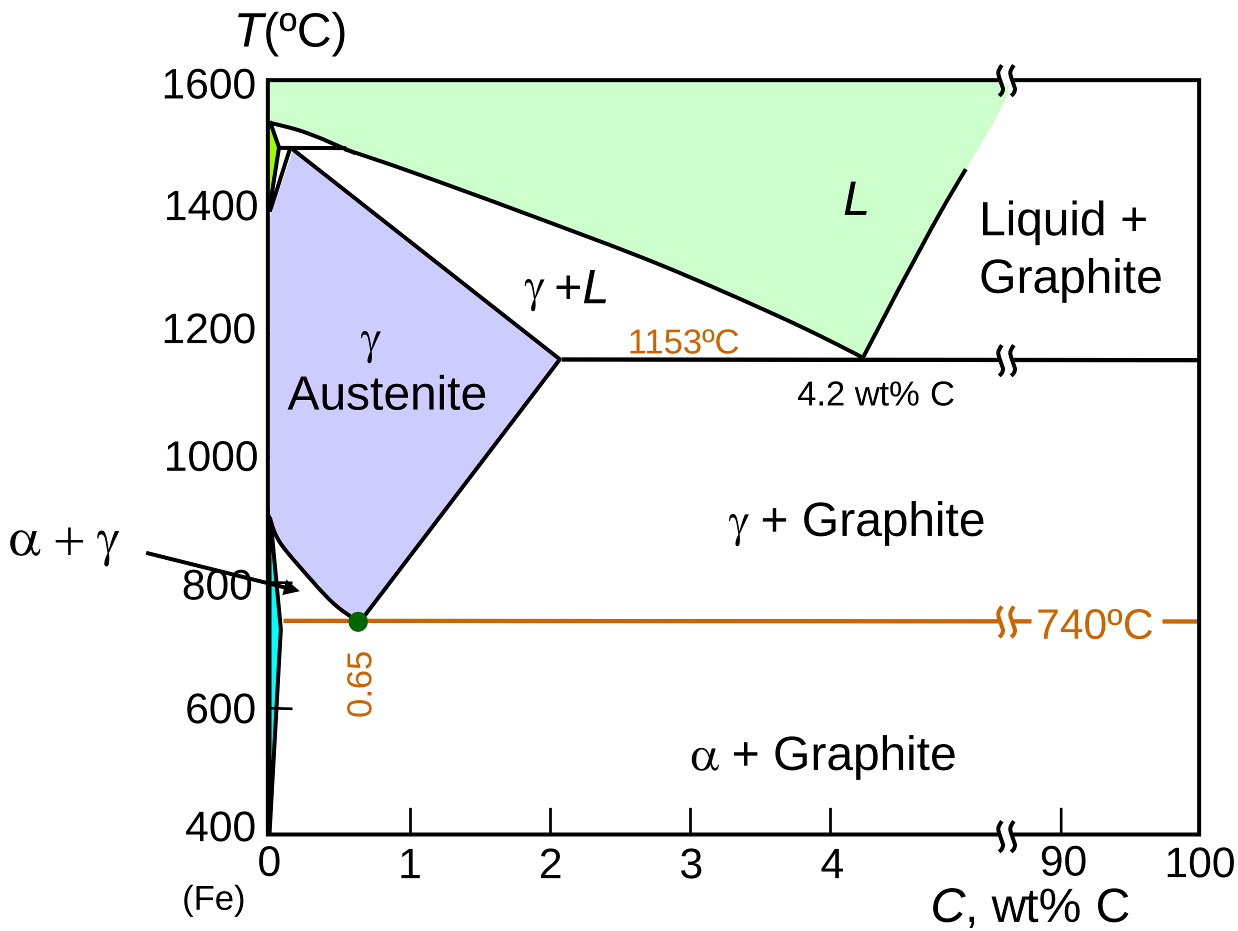
  $Fe_3C \rightarrow 3\ Fe\ (\alpha) + C\ (graphite)$

  - generally a slow process

Fe-C True Equilibrium Diagram

Graphite formation promoted by

- Si > 1 wt%
- slow cooling



Adapted from Fig. 11.2, *Callister & Rethwisch 8e.* [Fig. 11.2 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.]

Types of Cast Iron

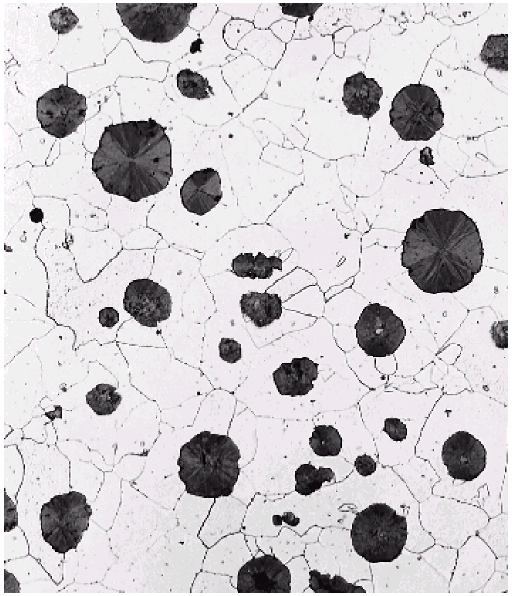
Adapted from Fig. 11.3(a) & (b), *Callister & Rethwisch 8e.*

Gray iron

- graphite flakes
- weak & brittle in tension
- stronger in compression
- excellent vibrational dampening
- wear resistant

Ductile iron

- add Mg and/or Ce
- graphite as nodules not flakes
- matrix often pearlite – stronger but less ductile



Types of Cast Iron (cont.)

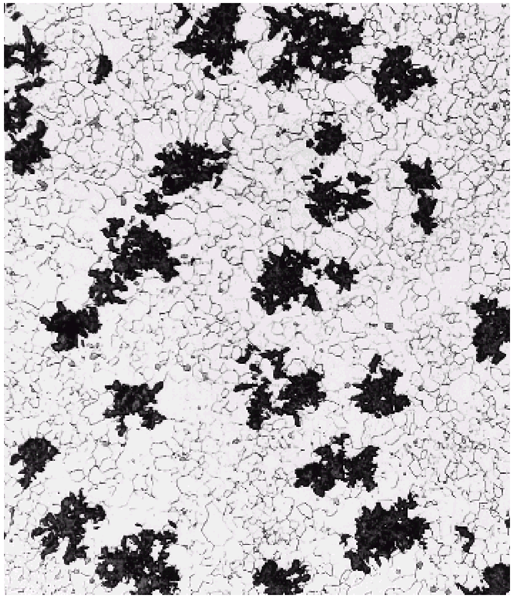
Adapted from Fig. 11.3(c) & (d), *Callister & Rethwisch 8e.*

White iron

- < 1 wt% Si
- pearlite + cementite
- very hard and brittle

Malleable iron

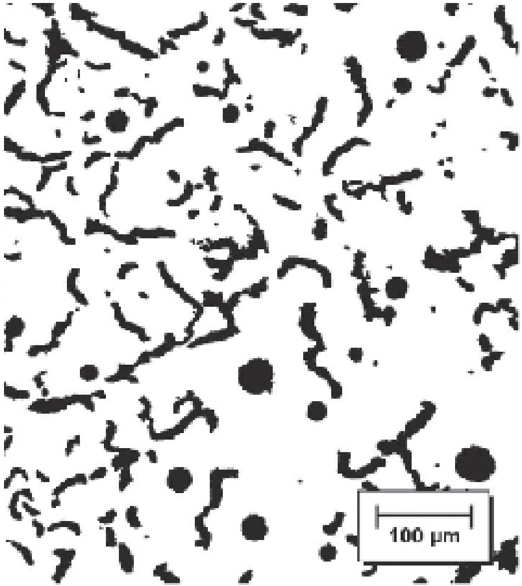
- heat treat white iron at 800-900ºC
- graphite in rosettes
- reasonably strong and ductile



Types of Cast Iron (cont.)

Compacted graphite iron

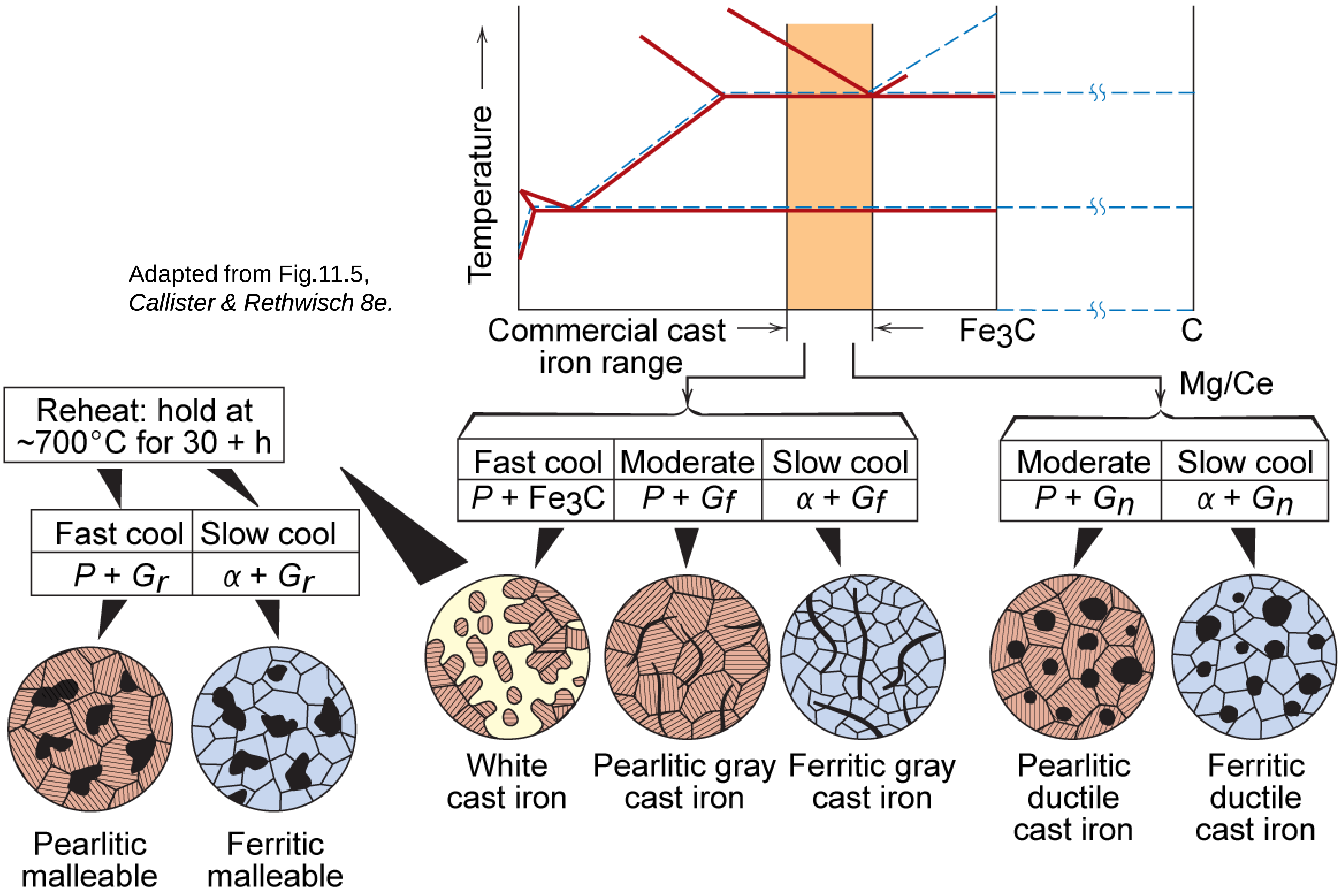
- relatively high thermal conductivity
- good resistance to thermal shock
- lower oxidation at elevated temperatures



Adapted from Fig. 11.3(e), *Callister & Rethwisch 8e.*

Production of Cast Irons

Adapted from Fig.11.5, *Callister & Rethwisch 8e.*



Limitations of Ferrous Alloys

1) Relatively high densities
2) Relatively low electrical conductivities
3) Generally poor corrosion resistance

Nonferrous Alloys

NonFerrous Alloys

- **Cu Alloys**

Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)

Bronze : Sn, Al, Si, Ni are subst. impurities (bushings, landing gear)

Cu-Be: precip. hardened for strength

- **Al Alloys**

-low ρ: 2.7 g/cm^3

-Cu, Mg, Si, Mn, Zn additions

-solid sol. or precip. strengthened (struct. aircraft parts & packaging)

- **Mg Alloys**

-very low ρ: 1.7g/cm^3

-ignites easily

-aircraft, missiles

- **Ti Alloys**

-relatively low ρ: 4.5 g/cm^3 vs 7.9 for steel

-reactive at high *T's*

-space applic.

- **Noble metals**

-Ag, Au, Pt

-oxid./corr. resistant

- **Refractory metals**

-high melting *T's*

-Nb, Mo, W, Ta

Based on discussion and data provided in Section 11.3, *Callister & Rethwisch 3e.*

Metal Fabrication

- How do we fabricate metals?
  – Blacksmith - hammer (forged)
  – Cast molten metal into mold

- Forming Operations
  – Rough stock formed to final shape

Hot working vs. Cold working

Hot working

- Deformation temperature high enough for recrystallization
- Large deformations

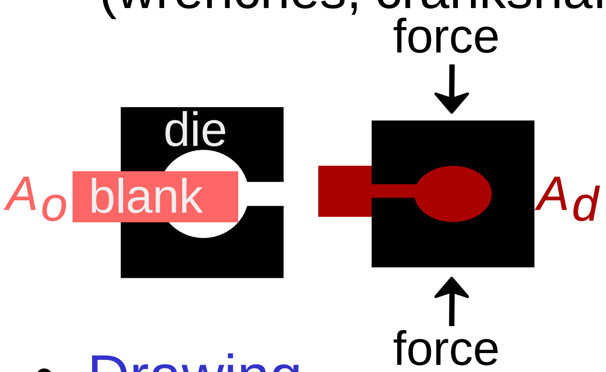
Cold working

- Deformation below recrystallization temperature
- Strain hardening occurs
- Small deformations

Metal Fabrication Methods (i)

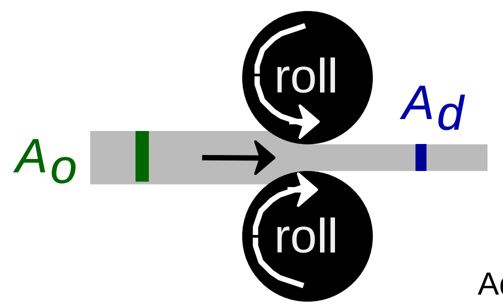
FORMING | CASTING | MISCELLANEOUS

- Forging (Hammering; Stamping)
  (wrenches, crankshafts)



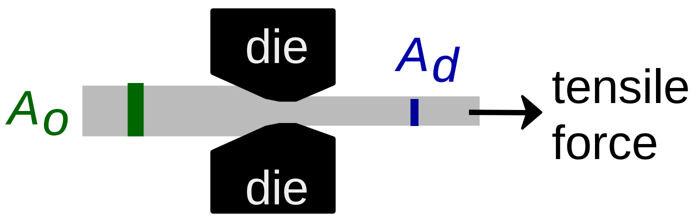
often at elev. *T*

- Rolling (Hot or Cold Rolling)
  (I-beams, rails, sheet & plate)



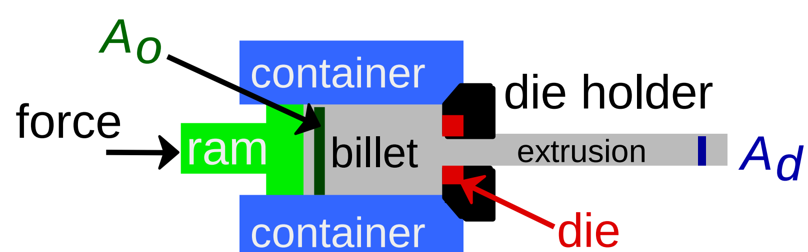
Adapted from Fig. 11.8, *Callister & Rethwisch 8e.*

- Drawing
  (rods, wire, tubing)



die must be well lubricated & clean

- Extrusion
  (rods, tubing)



ductile metals, e.g. Cu, Al (hot)

Metal Fabrication Methods (ii)

FORMING | CASTING | MISCELLANEOUS

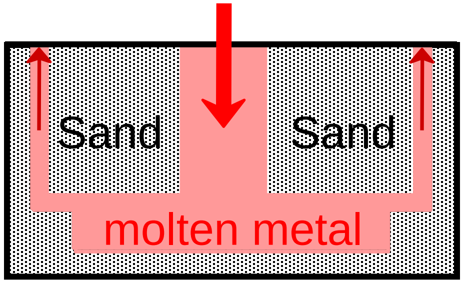
- Casting- mold is filled with molten metal
  - metal melted in furnace, perhaps alloying elements added, then cast in a mold
  - common and inexpensive
  - gives good production of shapes
  - weaker products, internal defects
  - good option for brittle materials

Metal Fabrication Methods (iii)

FORMING | **CASTING** | MISCELLANEOUS

- Sand Casting

  (large parts, e.g., auto engine blocks)



- What material will withstand T >1600ºC and is inexpensive and easy to mold?
- Answer: sand!!!
- To create mold, pack sand around form (pattern) of desired shape

Metal Fabrication Methods (iv)

FORMING | **CASTING** | MISCELLANEOUS

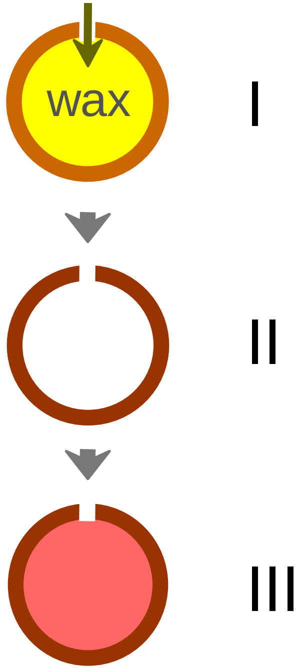
- Investment Casting

  (low volume, complex shapes
  e.g., jewelry, turbine blades)

- Stage I — Mold formed by pouring plaster of paris around wax pattern. Plaster allowed to harden.

- Stage II — Wax is melted and then poured from mold—hollow mold cavity remains.

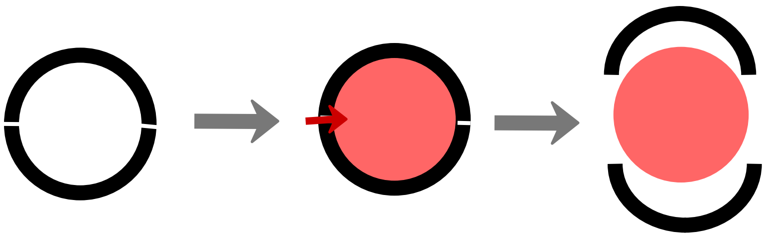
- Stage III — Molten metal is poured into mold and allowed to solidify.



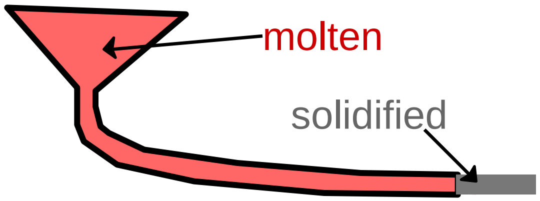
Metal Fabrication Methods (v)

FORMING | **CASTING** | MISCELLANEOUS

- Die Casting
  - -- high volume
  - -- for alloys having low melting temperatures



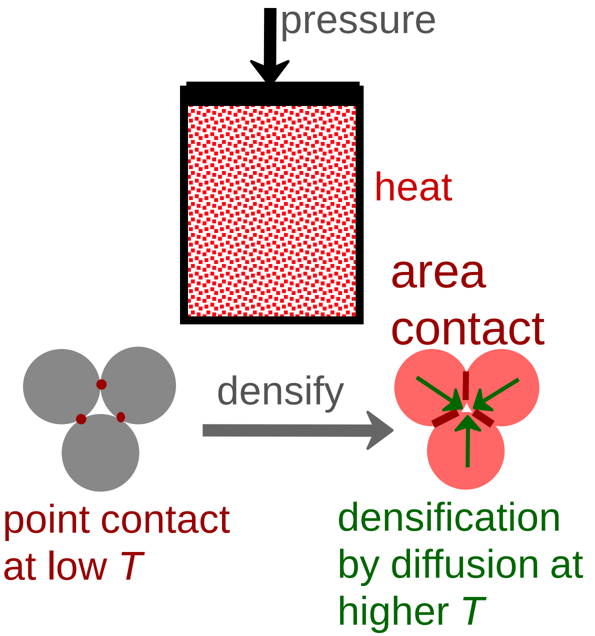
- Continuous Casting
  - -- simple shapes (e.g., rectangular slabs, cylinders)



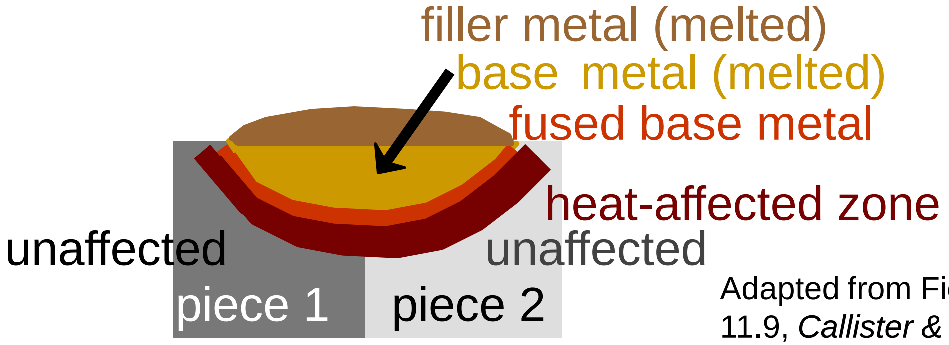
Metal Fabrication Methods (vi)

FORMING CASTING **MISCELLANEOUS**

- Powder Metallurgy
  (metals w/low ductilities)



- Welding
  (when fabrication of one large part is impractical)



Adapted from Fig. 11.9, *Callister & Rethwisch 8e.* (Fig. 11.9 from *Iron Castings Handbook*, C.F. Walton and T.J. Opar (Ed.), 1981.)

- Heat-affected zone:
  (region in which the microstructure has been changed).

Thermal Processing of Metals

Annealing: Heat to T_{anneal}, then cool slowly.

Types of Annealing

- **Stress Relief**: Reduce stresses resulting from:
  - plastic deformation
  - nonuniform cooling
  - phase transform.
- **Spheroidize** (steels): Make very soft steels for good machining. Heat just below $T_{eutectoid}$ & hold for 15-25 h.
- **Full Anneal** (steels): Make soft steels for good forming. Heat to get γ, then furnace-cool to obtain coarse pearlite.
- **Process Anneal**: Negate effects of cold working by (recovery/ recrystallization)
- **Normalize** (steels): Deform steel with large grains. Then heat treat to allow recrystallization and formation of smaller grains.

Based on discussion in Section 11.7, *Callister & Rethwisch 8e*.

Heat Treatment Temperature-Time Paths

a) Full Annealing

b) Quenching

c) Tempering (Tempered Martensite)

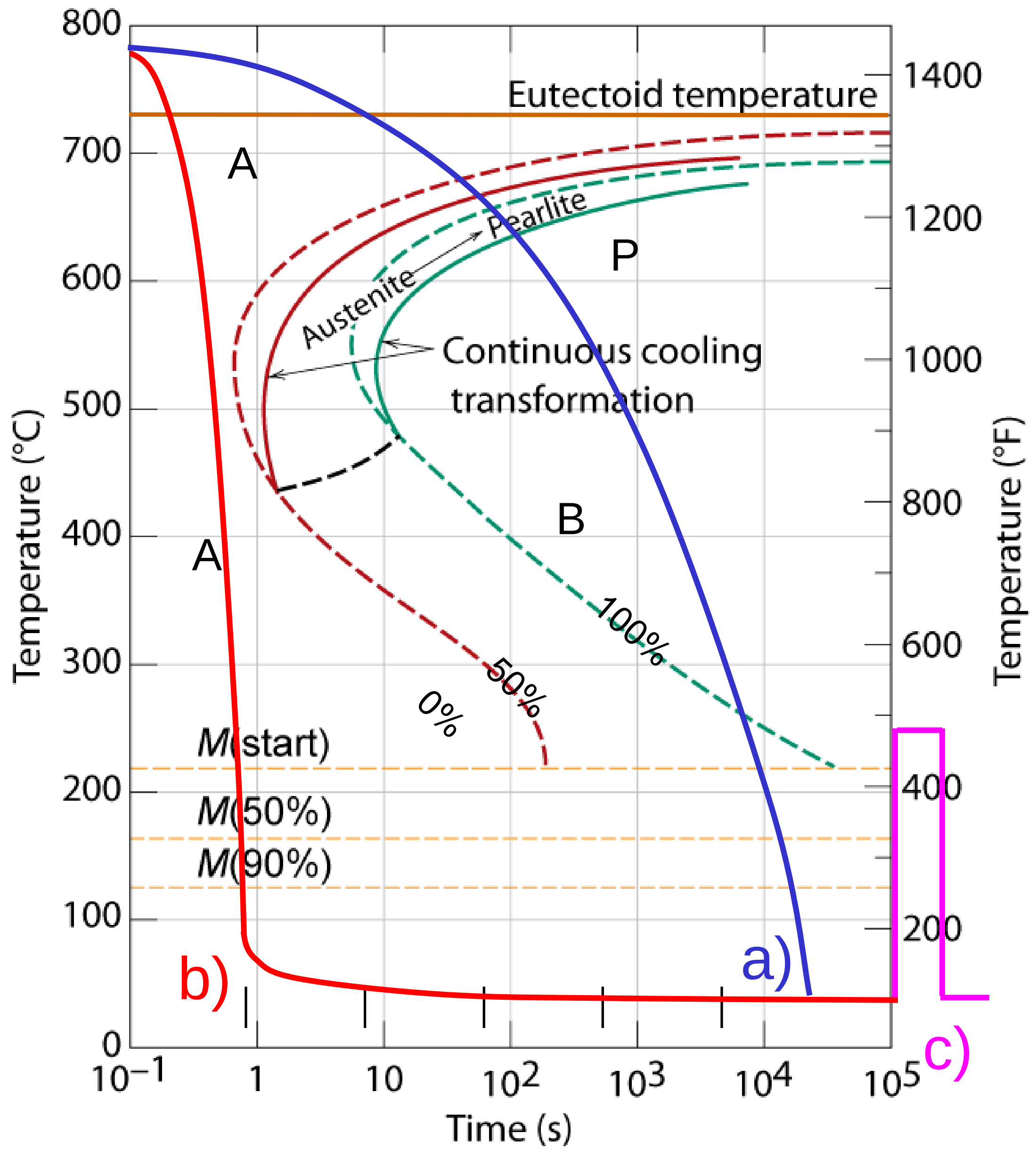
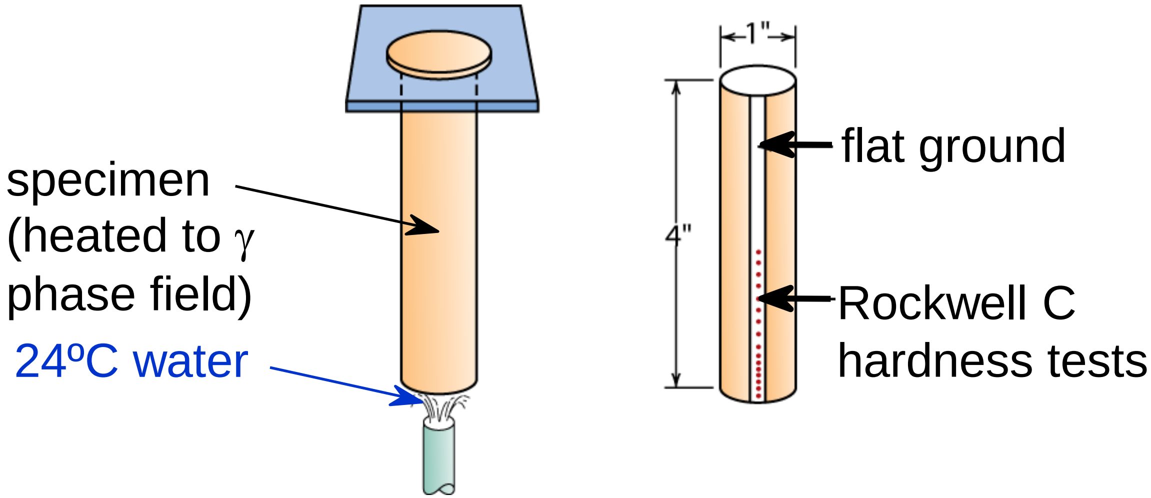


Fig. 10.25, *Callister & Rethwisch 8e*.

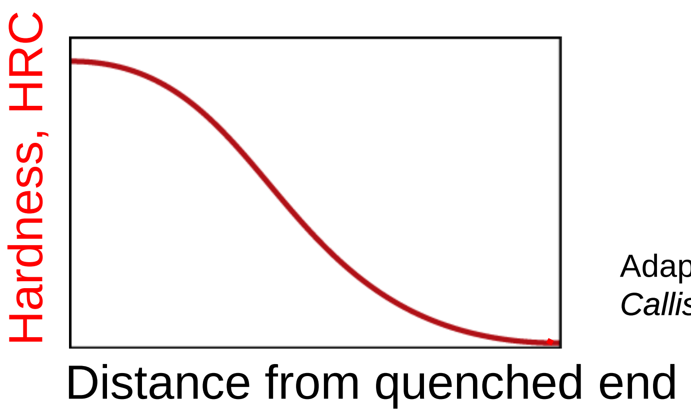
Hardenability -- Steels

- Hardenability – measure of the ability to form martensite
- Jominy end quench test used to measure hardenability.



Adapted from Fig. 11.11, *Callister & Rethwisch 8e*. (Fig. 11.11 adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1978.)

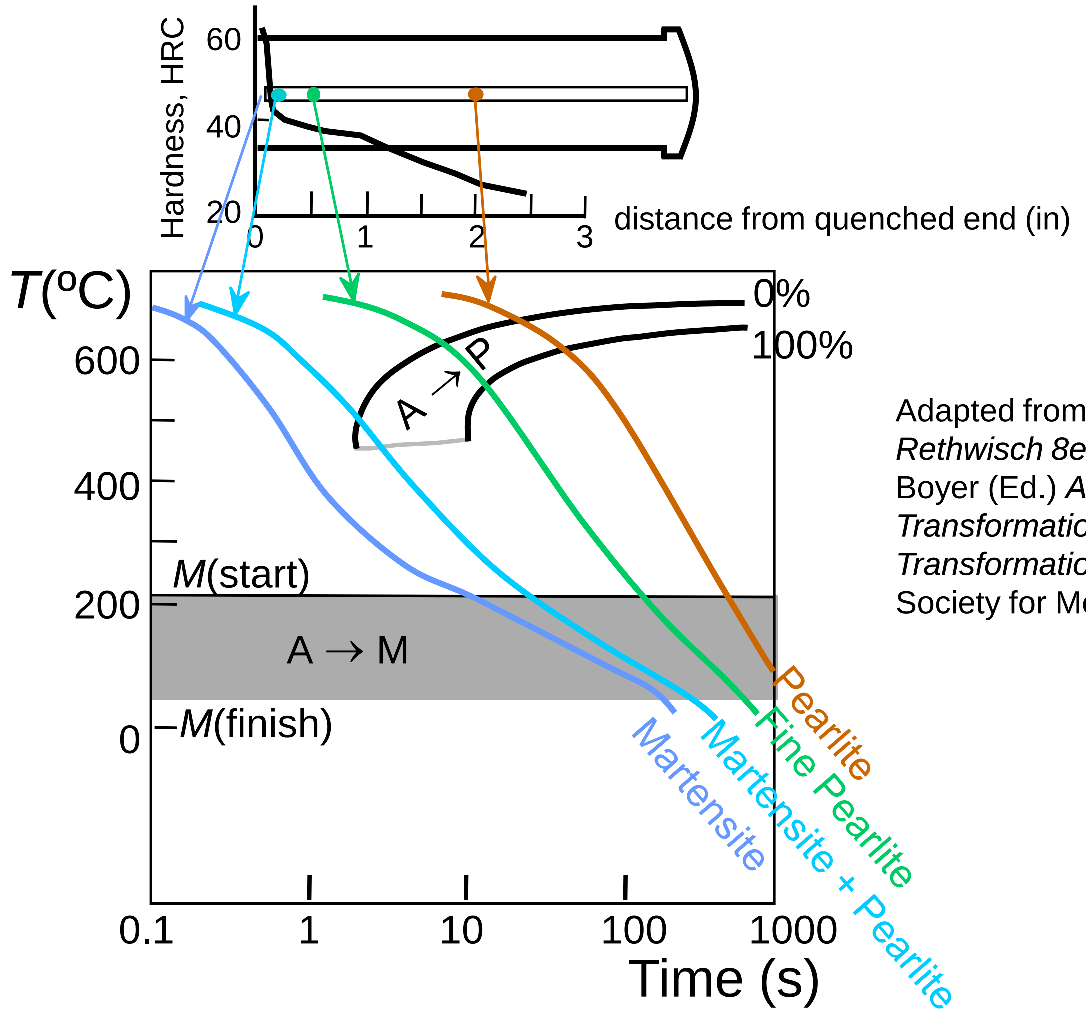
- Plot hardness versus distance from the quenched end.



Adapted from Fig. 11.12, *Callister & Rethwisch 8e*.

Reason Why Hardness Changes with Distance

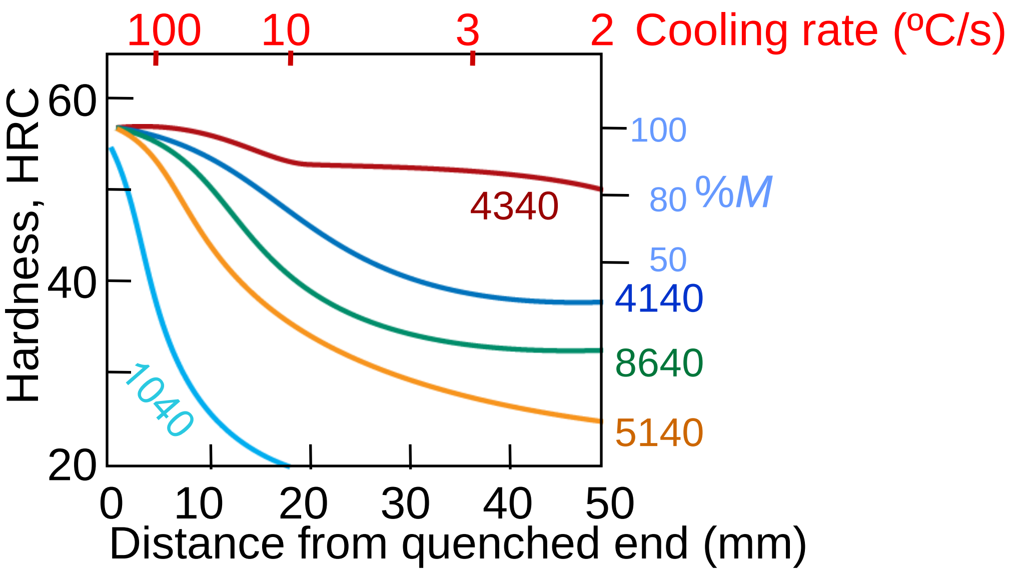
- The cooling rate decreases with distance from quenched end.



Adapted from Fig. 11.13, *Callister & Rethwisch 8e*. (Fig. 11.13 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 376.)

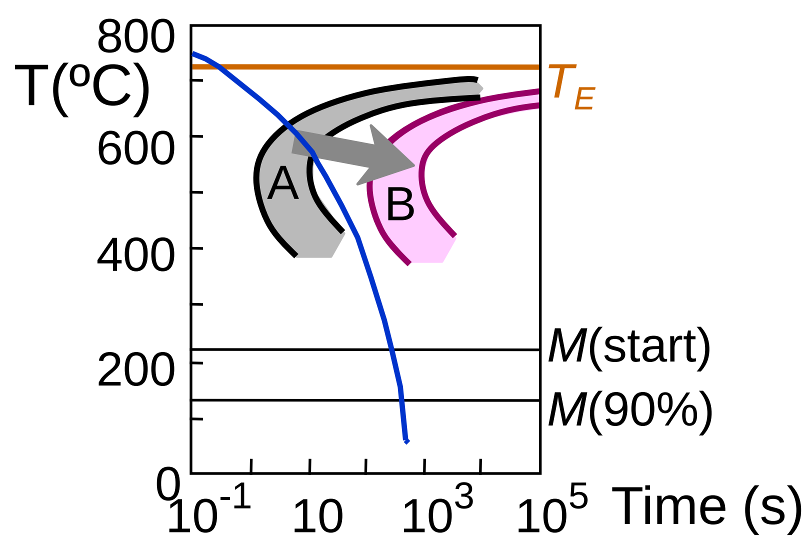
Hardenability vs Alloy Composition

- Hardenability curves for five alloys each with, $C = 0.4$ wt% C



Adapted from Fig. 11.14, *Callister & Rethwisch 8e*. (Fig. 11.14 adapted from figure furnished courtesy Republic Steel Corporation.)

- "Alloy Steels" (4140, 4340, 5140, 8640)
  - -- contain Ni, Cr, Mo (0.2 to 2 wt%)
  - -- these elements shift the "nose" to longer times (from A to B)
  - -- martensite is easier to form



Influences of Quenching Medium & Specimen Geometry

- Effect of quenching medium:

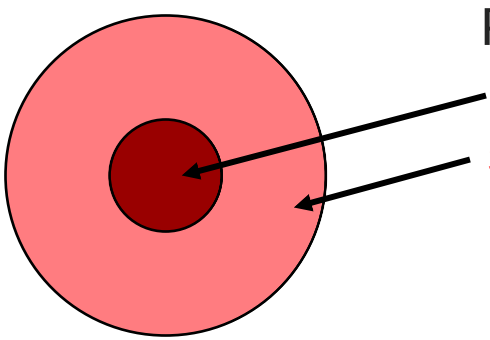
Medium	Severity of Quench	Hardness
air	low	low
oil	moderate	moderate
water	high	high

- Effect of specimen geometry:

When surface area-to-volume ratio increases:

-- cooling rate throughout interior increases

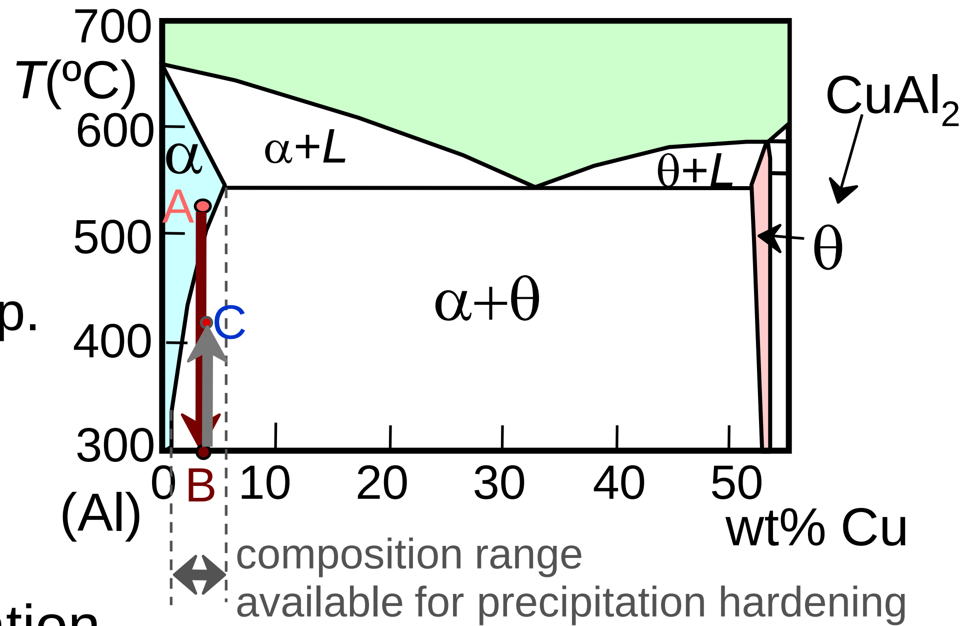
-- hardness throughout interior increases



Position	Cooling rate	Hardness
center	low	low
surface	high	high

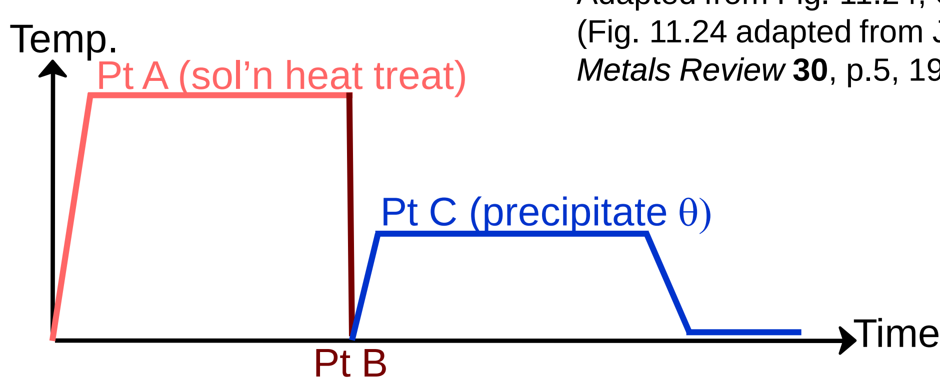
Precipitation Hardening

- Particles impede dislocation motion.
- Ex: Al-Cu system
- Procedure:
  -- Pt A: solution heat treat
  (get α solid solution)
  -- Pt B: quench to room temp.
  (retain α solid solution)
  -- Pt C: reheat to nucleate
  small θ particles within
  α phase.



Adapted from Fig. 11.24, *Callister & Rethwisch 8e*. (Fig. 11.24 adapted from J.L. Murray, *International Metals Review* **30**, p.5, 1985.)

- Other alloys that precipitation
  harden:
  - Cu-Be
  - Cu-Sn
  - Mg-Al



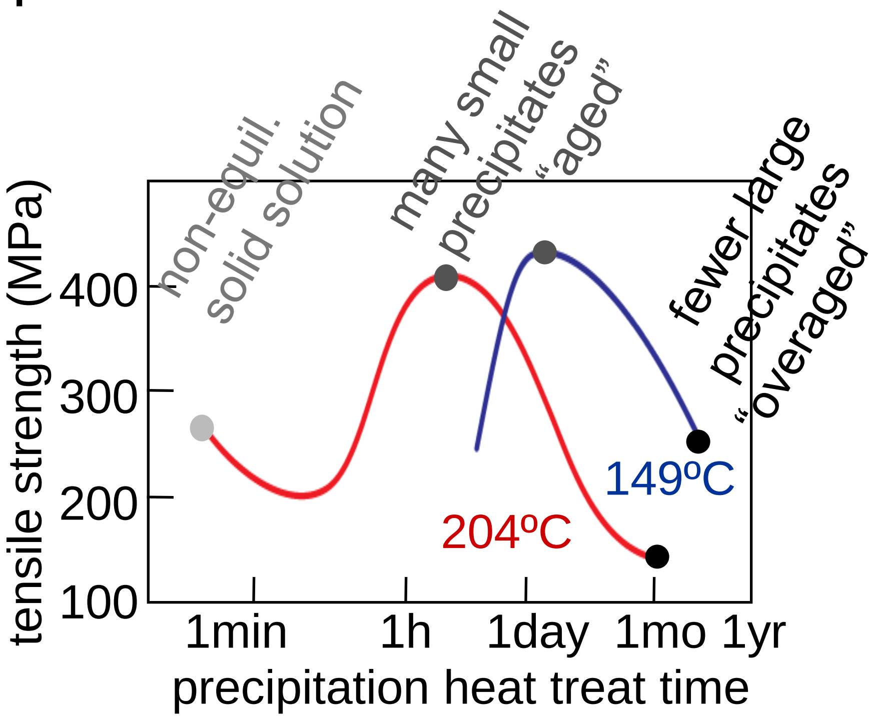
Adapted from Fig. 11.22, *Callister & Rethwisch 8e*.

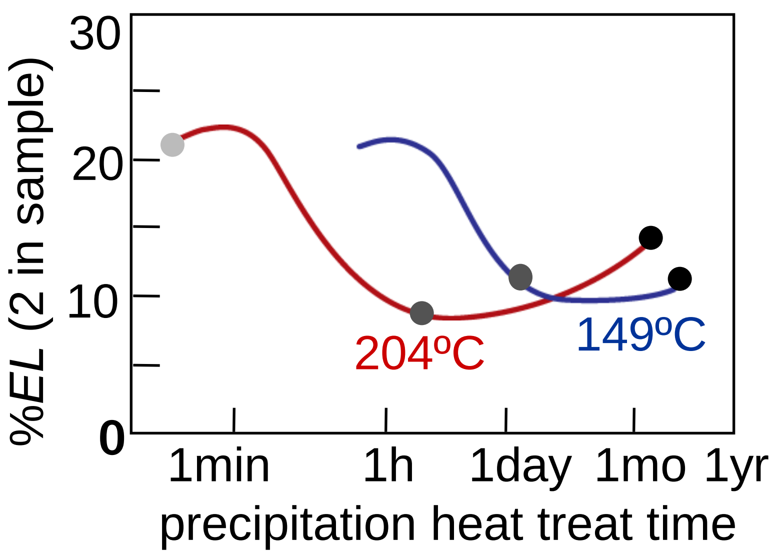
Influence of Precipitation Heat Treatment on *TS*, *%EL*

- 2014 Al Alloy:

- Maxima on *TS* curves.
- Increasing *T* accelerates process.

- Minima on %*EL* curves.





Adapted from Fig. 11.27, *Callister & Rethwisch 8e*. (Fig. 11.27 adapted from *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), American Society for Metals, 1979. p. 41.)

Summary

- Ferrous alloys: steels and cast irons
- Non-ferrous alloys:
  -- Cu, Al, Ti, and Mg alloys; refractory alloys; and noble metals.
- Metal fabrication techniques:
  -- forming, casting, miscellaneous.
- Hardenability of metals
  -- measure of ability of a steel to be heat treated.
  -- increases with alloy content.
- Precipitation hardening
  --hardening, strengthening due to formation of precipitate particles.
  --Al, Mg alloys precipitation hardenable.