Chemical Engineering 378

Science of Materials Engineering

Lecture 24

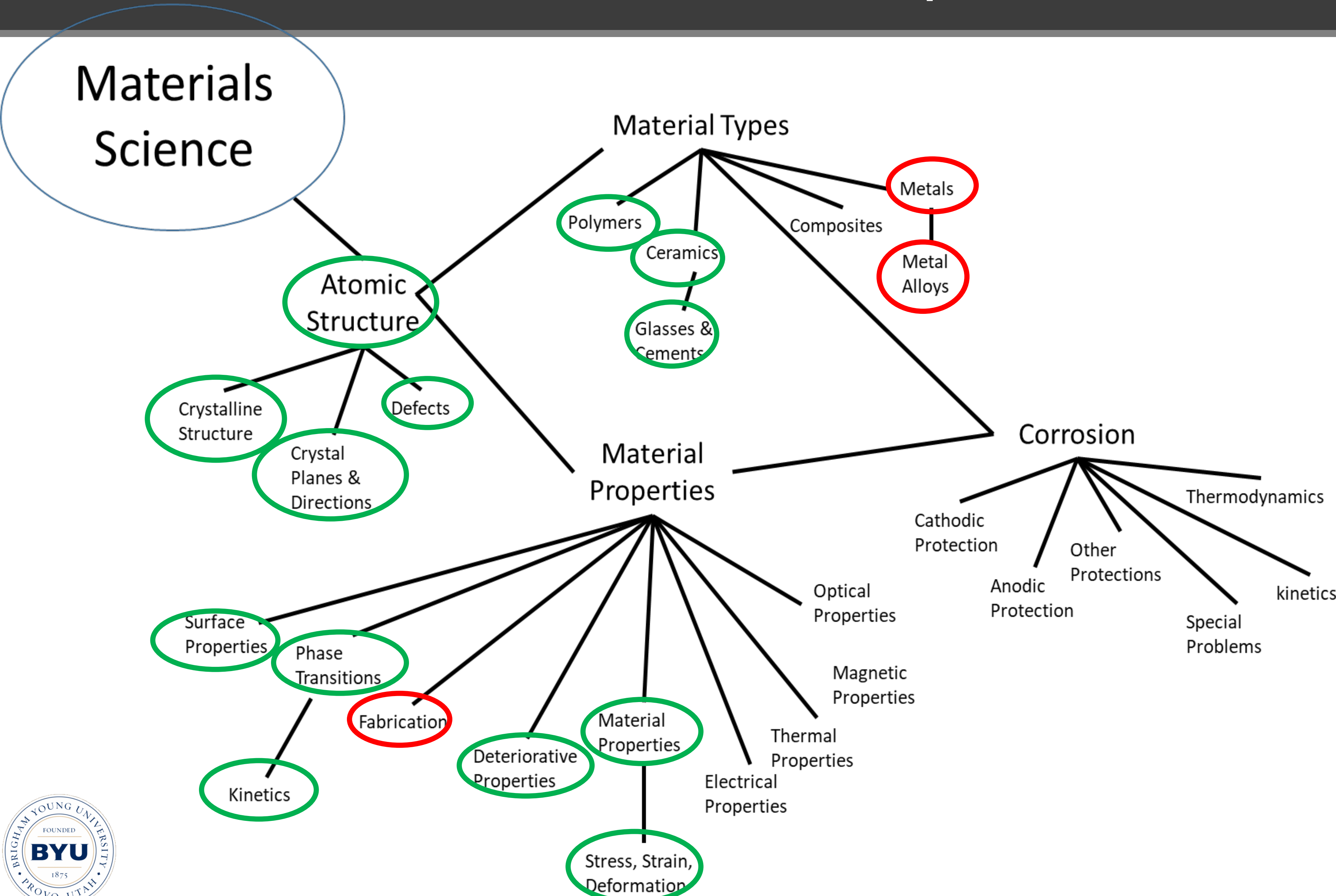
Various Metals, Processing

Spiritual Thought

"I urge you to not take counsel of your fears. I hope you will not say, "I'm not smart enough to study chemical engineering; hence, I'll study something less strenuous." "I can't apply myself sufficiently well to study this difficult subject or in this comprehensive field; hence, I'll choose the easier way." I plead with you to choose the hard way and tax your talents. Our Heavenly Father will make you equal to your tasks. If one should stumble, if one should take a course and get less than the "A" grade desired, I hope such a one will not let it become a discouraging thing to him. I hope that he will rise and try again."

President Thomas S. Monson

Materials Roadmap



Classification of Metal Alloys

Metal Alloys

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

microstructure: ferrite, graphite/cementite

Adapted from Fig. 11.1, *Callister & Rethwisch 10e.*

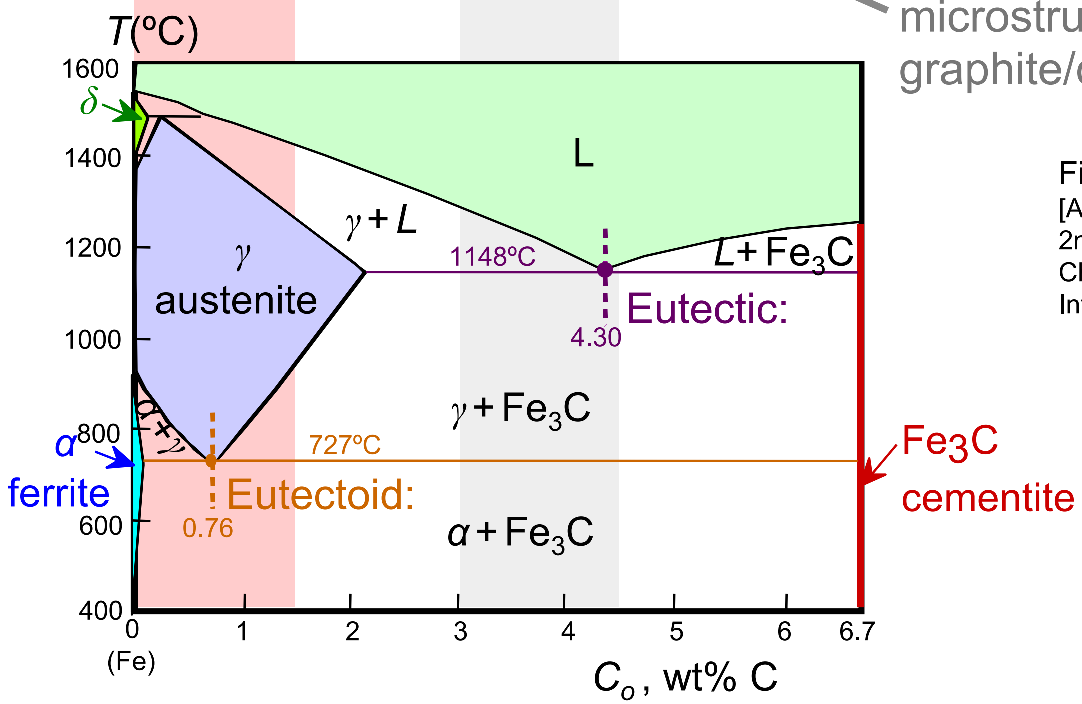


Fig. 9.24, *Callister & Rethwisch 10e*. [Adapted from Binary Alloy Phase Diagrams, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

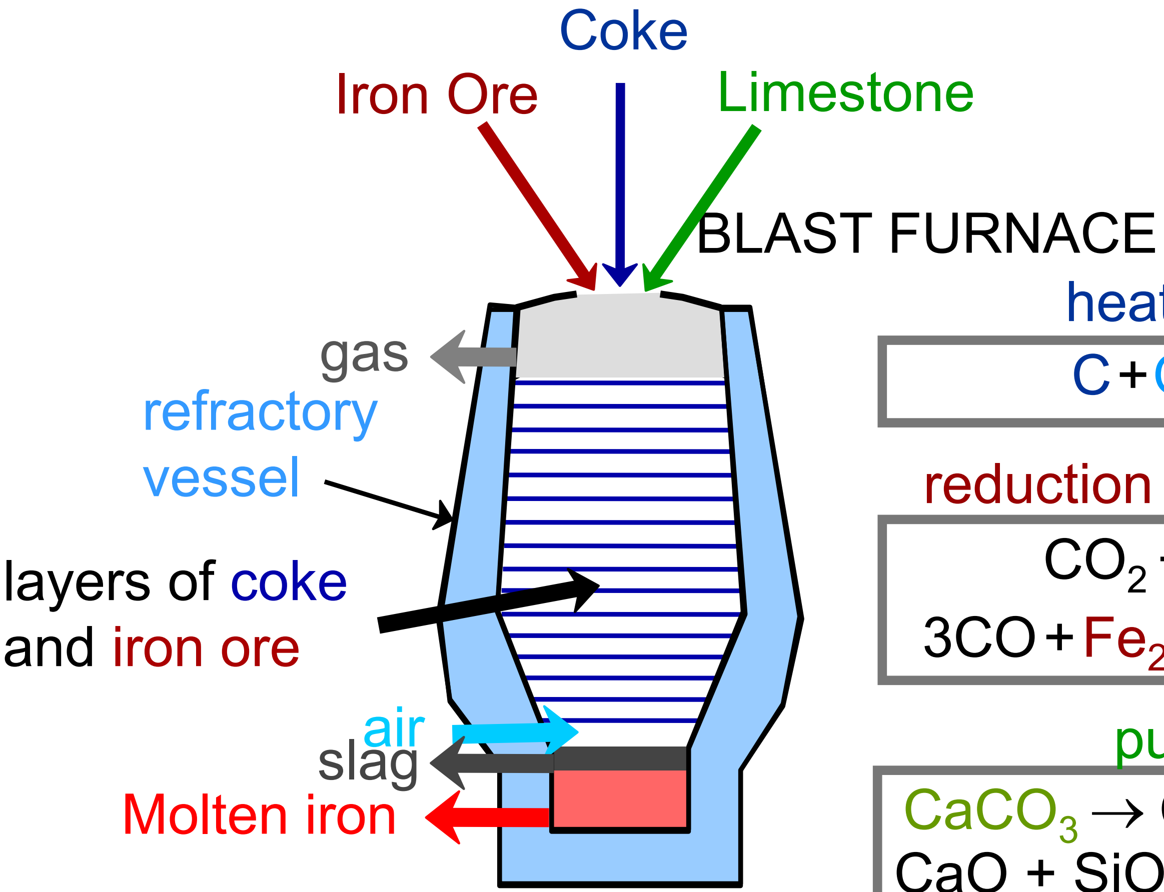
Steels

	Low Alloy						High Alloy
	low carbon <0.25 wt% C		Med carbon 0.25-0.6 wt% C		high carbon 0.6-1.4 wt% C		
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), 11.3, and 11.4, *Callister & Rethwisch 10e.*

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

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

  - generally a slow process

Fe-C True Equilibrium Diagram

Graphite formation promoted by

- Si > 1 wt%
- slow cooling

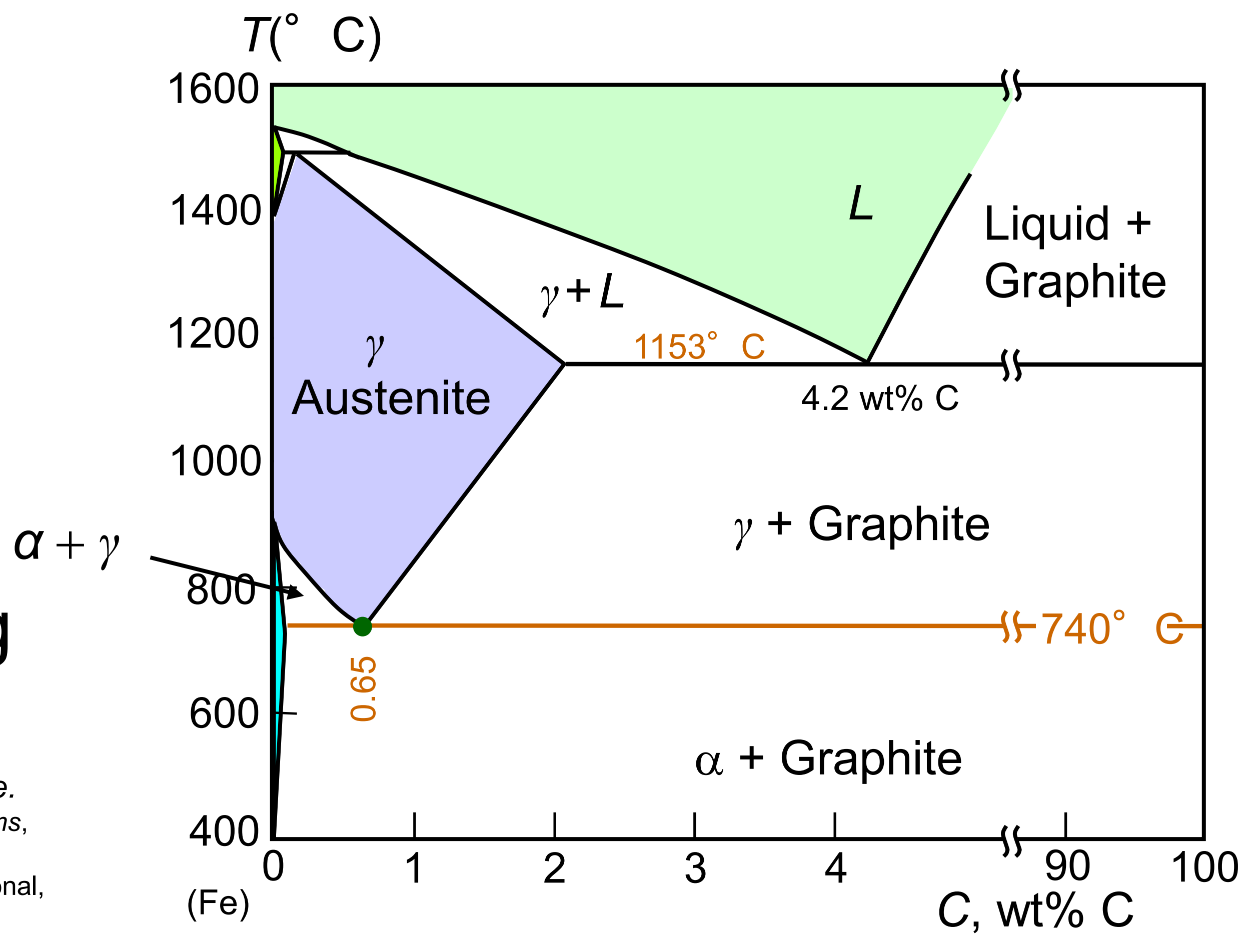


Fig. 11.2, *Callister & Rethwisch 10e.* [Adapted from *Binary Alloy Phase Diagrams*, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Types of Cast Iron

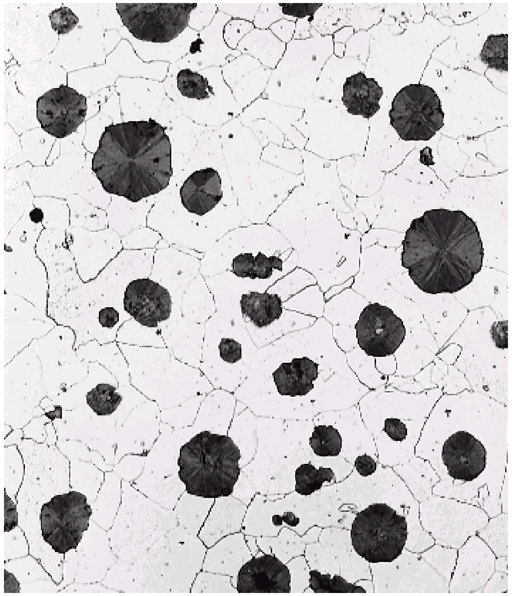
Gray iron

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

Figs. 11.3(a) & (b), *Callister & Rethwisch 10e.* [Courtesy of C. H. Brady and L. C. Smith, National Bureau of Standards, Washington, DC (now the National Institute of Standards and Technology, Gaithersburg, MD)]

Ductile iron

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



Types of Cast Iron (cont.)

Figs. 11.3(c) & (d), *Callister & Rethwisch 10e.*

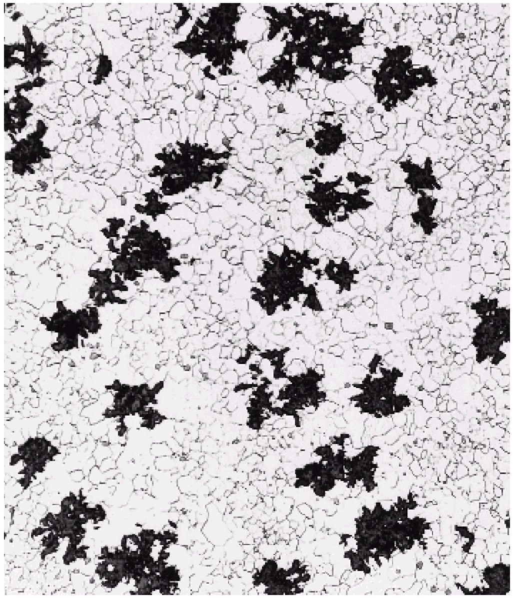
White iron

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

Courtesy of Amcast Industrial Corporation

Malleable iron

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



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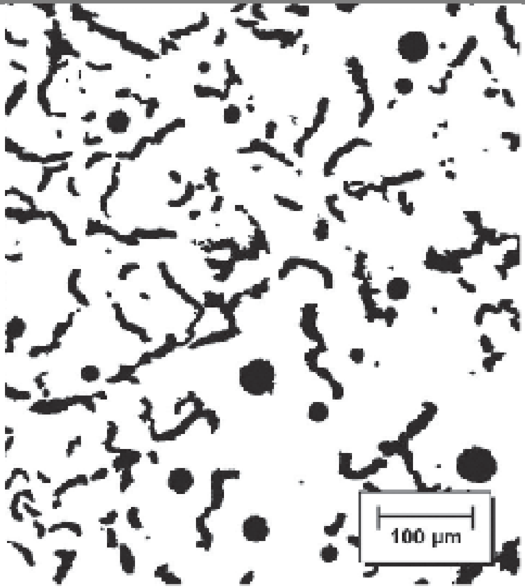
Types of Cast Iron (cont.)

Compacted graphite iron

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

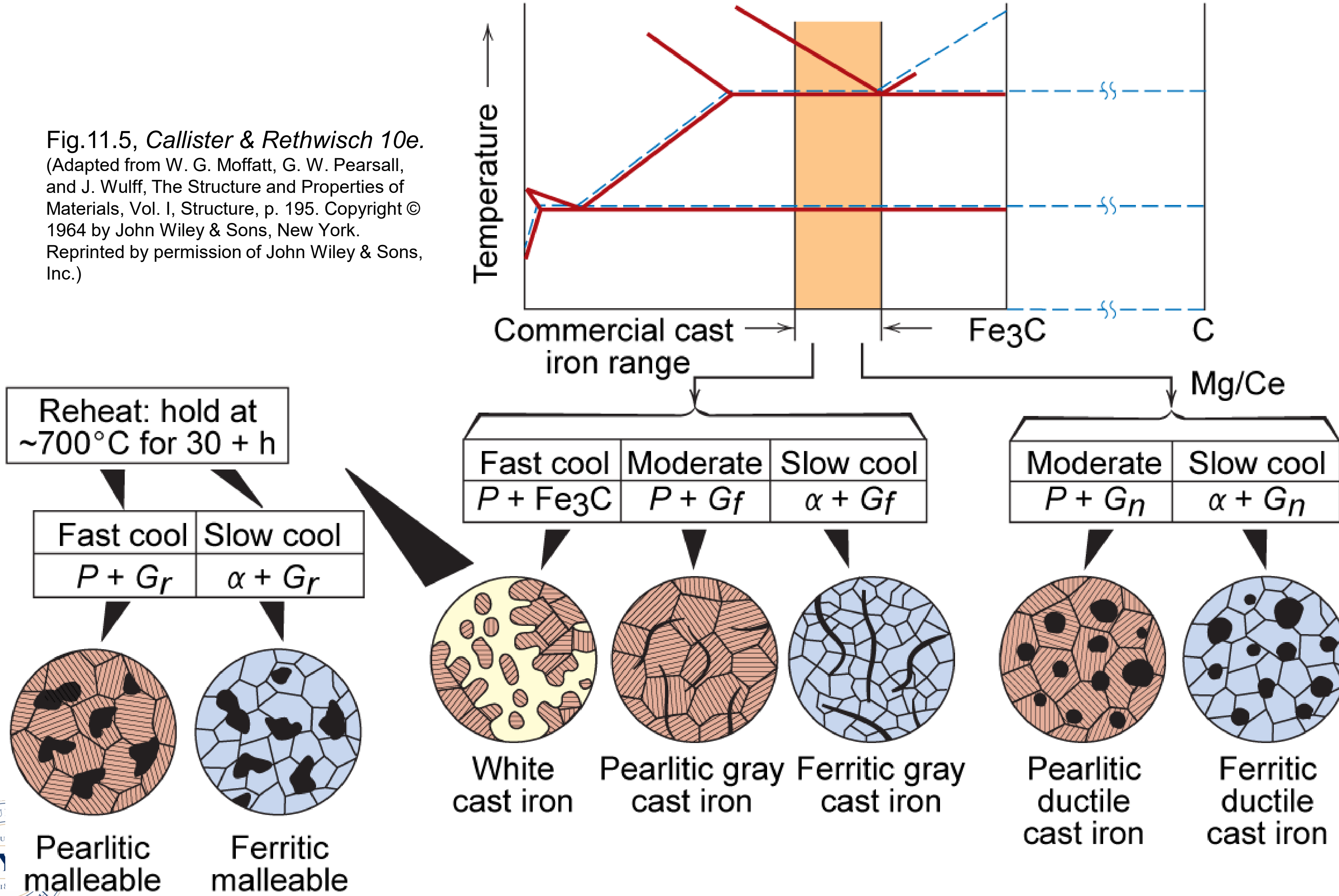


Courtesy of Sinter-Cast, Ltd.

Fig. 11.3(e), *Callister & Rethwisch 10e.*

Production of Cast Irons

Fig.11.5, *Callister & Rethwisch 10e.* (Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, The Structure and Properties of Materials, Vol. I, Structure, p. 195. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



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: 1.7 g/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 10e.*

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

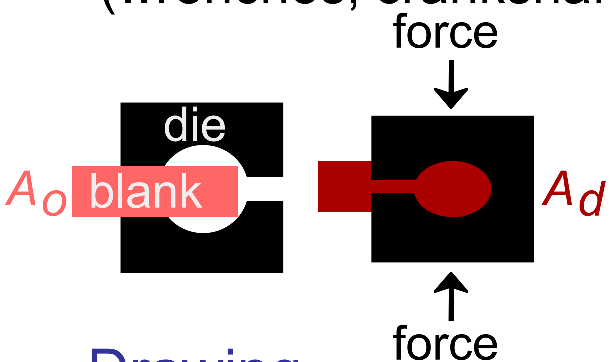
Cold working:

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

Metal Fabrication Methods (i)

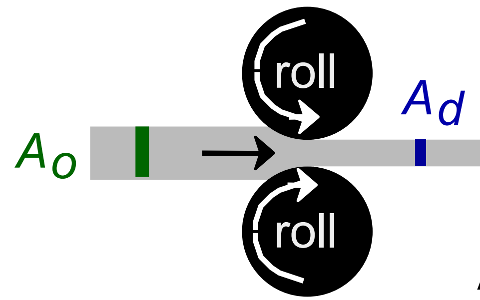
FORMING | CASTING | MISCELLANEOUS

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



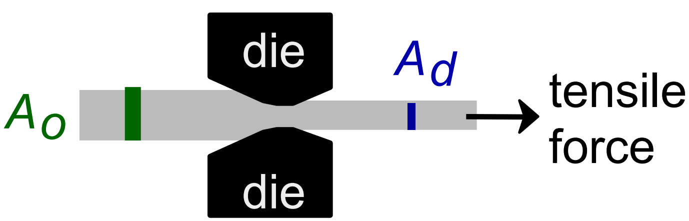
often at elev. T

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



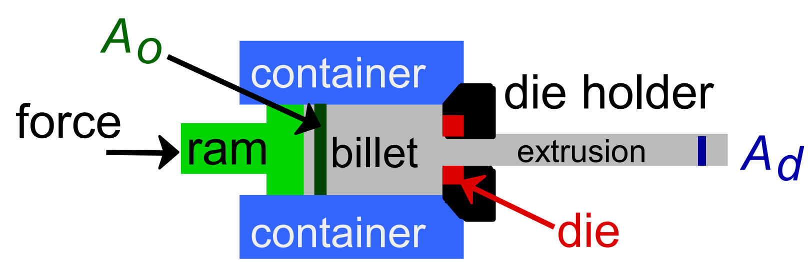
Adapted from Fig. 11.9, *Callister & Rethwisch 10e.*

- 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

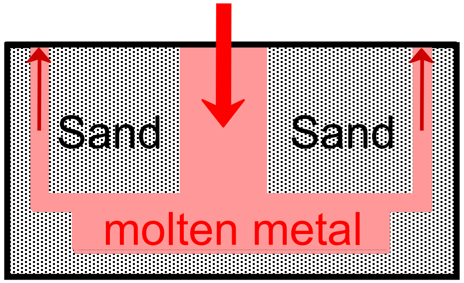
- Casting- mold is filled with molten metal
  - metal melted in furnace, perhaps alloying elements added, then cast in a mold
  - common and inexpensive
  - gives good production of shapes
  - weaker products, internal defects
  - good option for brittle materials

Metal Fabrication Methods (iii)

FORMING | **CASTING** | MISCELLANEOUS

- Sand Casting

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

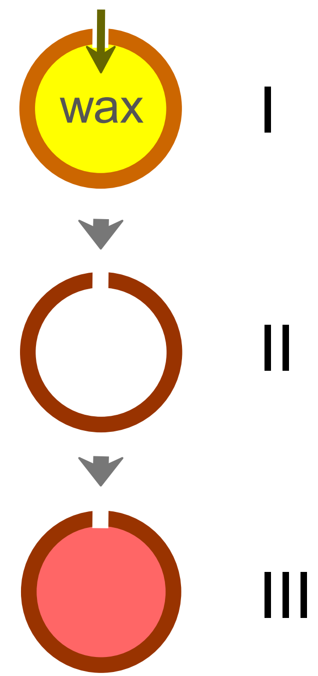


- What material will withstand T >1600° C and is inexpensive and easy to mold?
- Answer: sand!!!
- To create mold, pack sand around form (pattern) of desired shape

Metal Fabrication Methods (iv)

FORMING | **CASTING** | MISCELLANEOUS

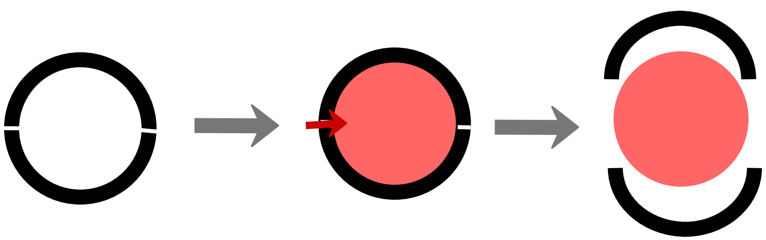
- Investment Casting
  (low volume, complex shapes
  e.g., jewelry, turbine blades)
  - Stage I — Mold formed by pouring plaster of paris around wax pattern. Plaster allowed to harden.
  - Stage II — Wax is melted and then poured from mold—hollow mold cavity remains.
  - Stage III — Molten metal is poured into mold and allowed to solidify.



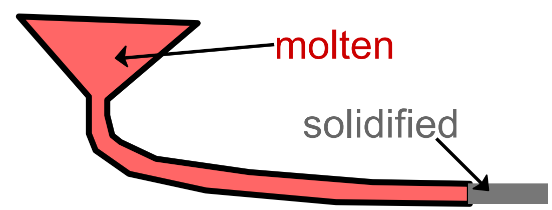
Metal Fabrication Methods (v)

FORMING | **CASTING** | MISCELLANEOUS

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



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

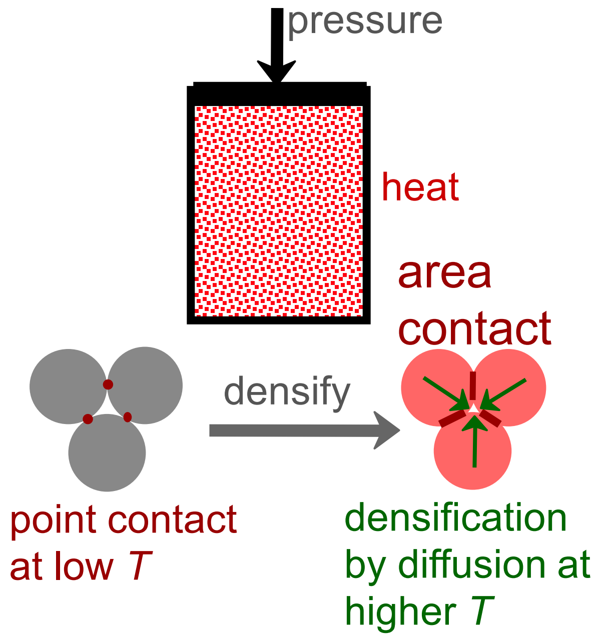


Metal Fabrication Methods (vi)

FORMING CASTING MISCELLANEOUS

- Powder Metallurgy

(metals w/low ductilities)



- Welding

(when fabrication of one large part is impractical)

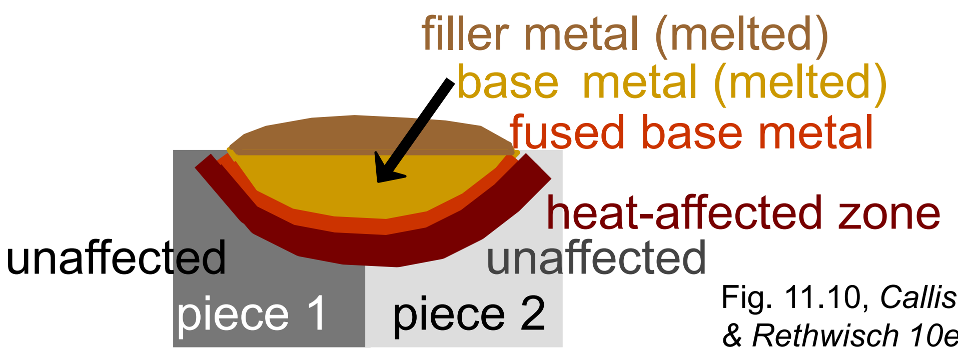


Fig. 11.10, *Callister & Rethwisch 10e.* [From *Iron Castings Handbook*, C.F. Walton and T.J. Opar (Ed.), Iron Castings Society, Des Plaines, IL,1981.]

- 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 11.8, *Callister & Rethwisch 10e*.

Heat Treatment Temperature-Time Paths

a) Full Annealing

b) Quenching

c) Tempering (Tempered Martensite)

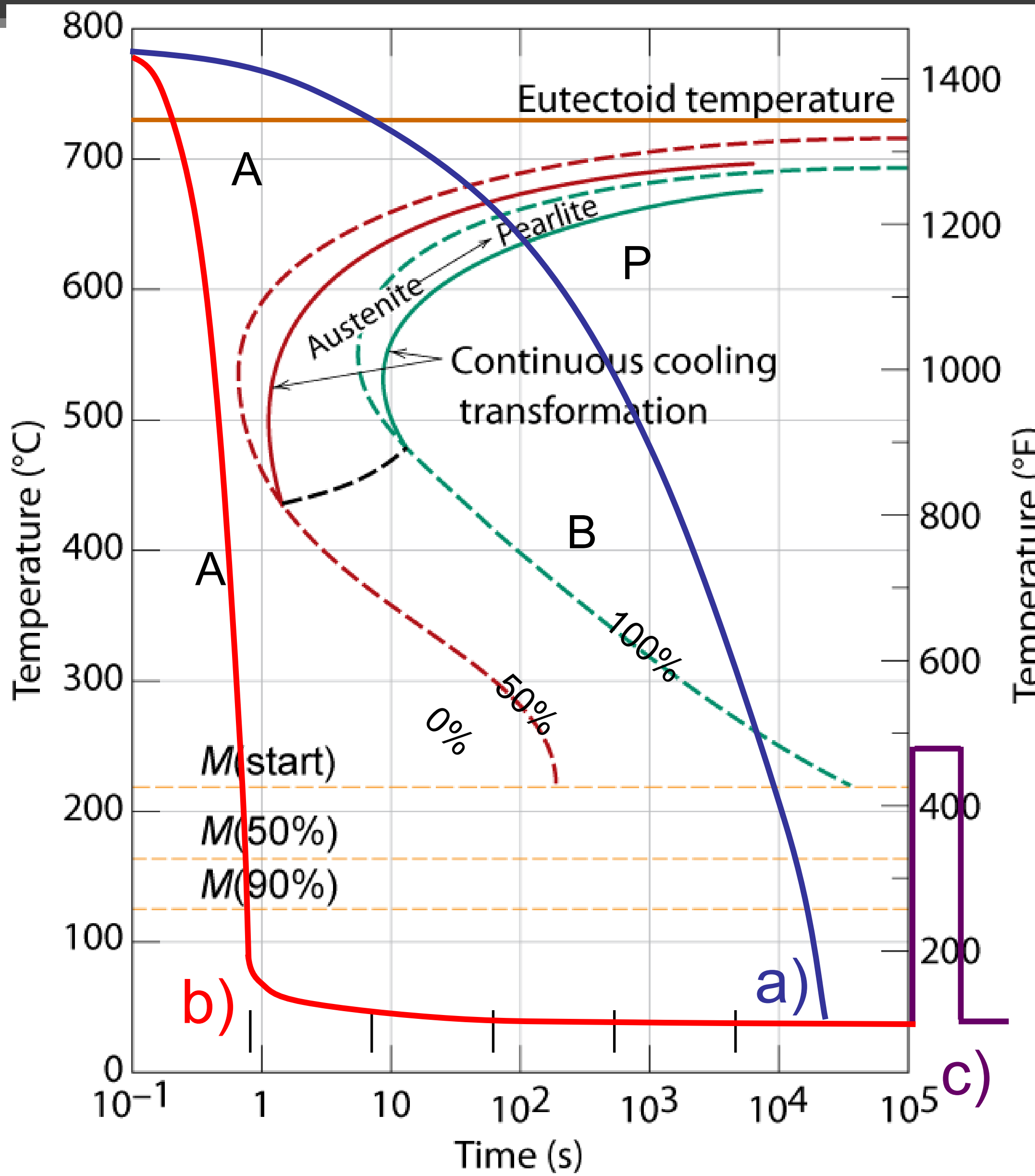


Fig. 10.25, *Callister & Rethwisch 10e*. [Adapted from H. Boyer (Editor), Atlas of Isothermal Transformation and Cooling Transformation Diagrams, 1977. Reproduced by permission of ASM International, Materials Park, OH.]

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

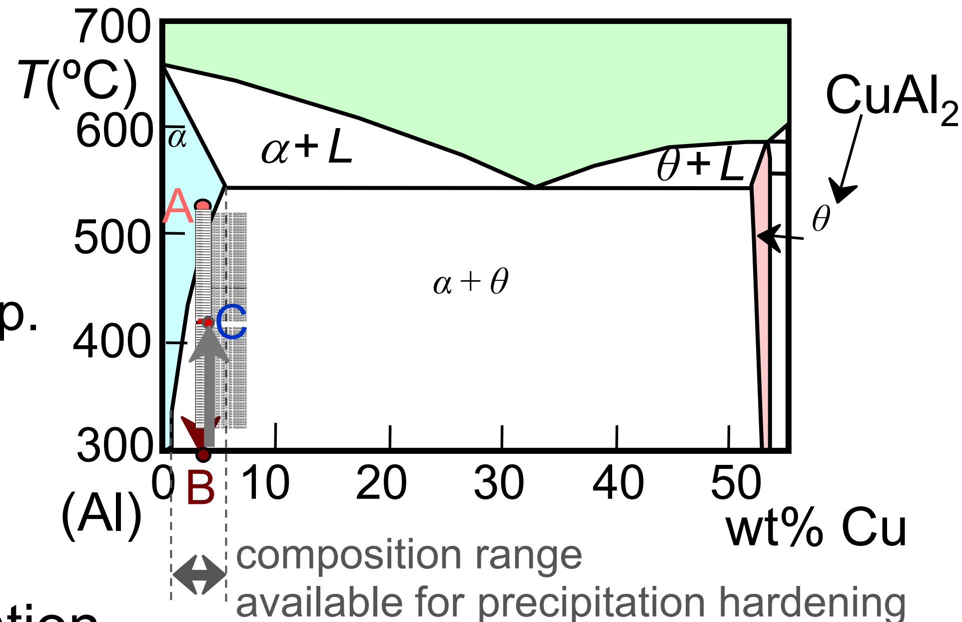
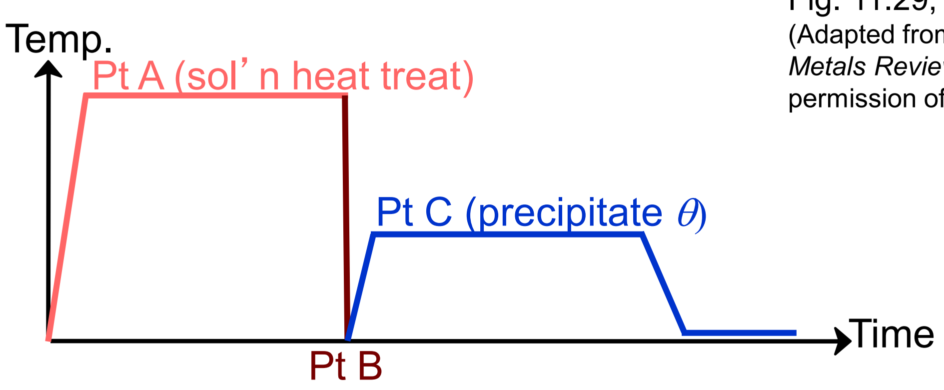


Fig. 11.29, *Callister & Rethwisch 10e*. (Adapted from J.L. Murray, *International Metals Review* **30**, p.5, 1985. Reprinted by permission of ASM International.)



Adapted from Fig. 11.27, *Callister & Rethwisch 10e*.

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

- 2014 Al Alloy:

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

- Minima on %*EL* curves.

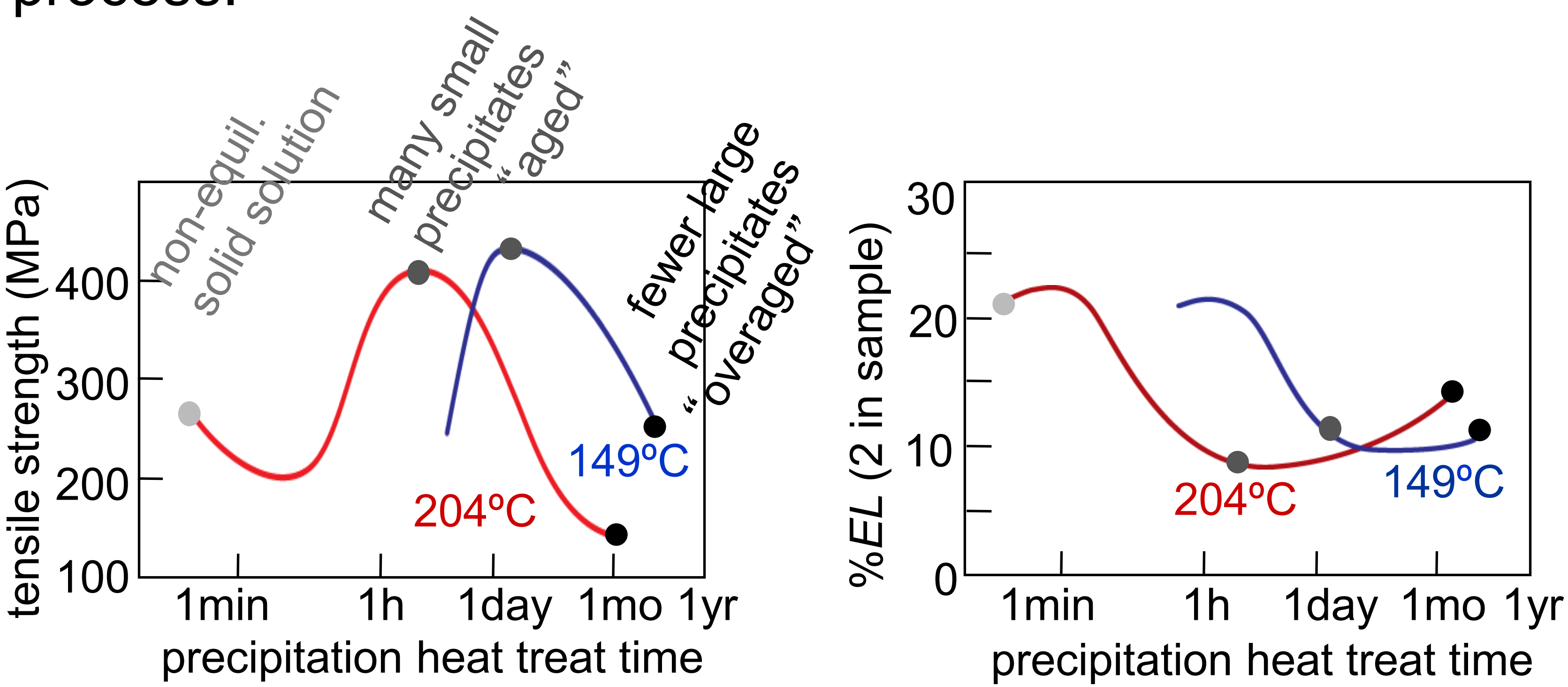


Fig. 11.32, *Callister & Rethwisch 10e*. [Adapted from *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th ed., H. Baker (Managing Ed.), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

Hardenability -- Steels

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

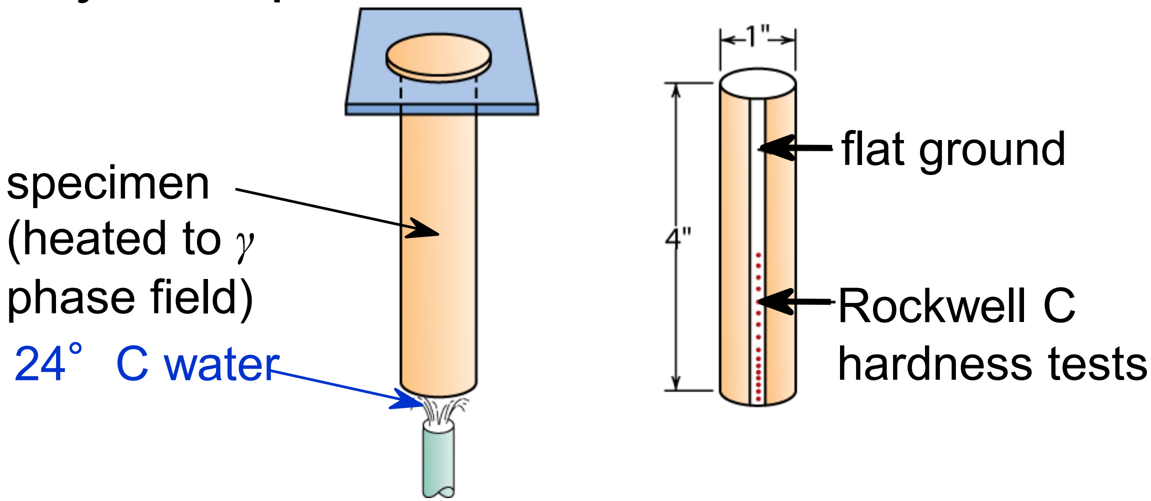


Fig. 11.15, *Callister & Rethwisch 10e*.
(Adapted from A.G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1978.)

- Plot hardness versus distance from the quenched end.

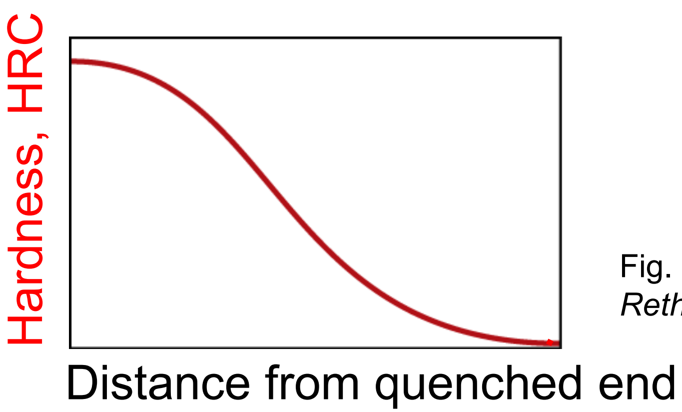


Fig. 11.16, *Callister & Rethwisch 10e*.

Reason Why Hardness Changes with Distance

- The cooling rate decreases with distance from quenched end.

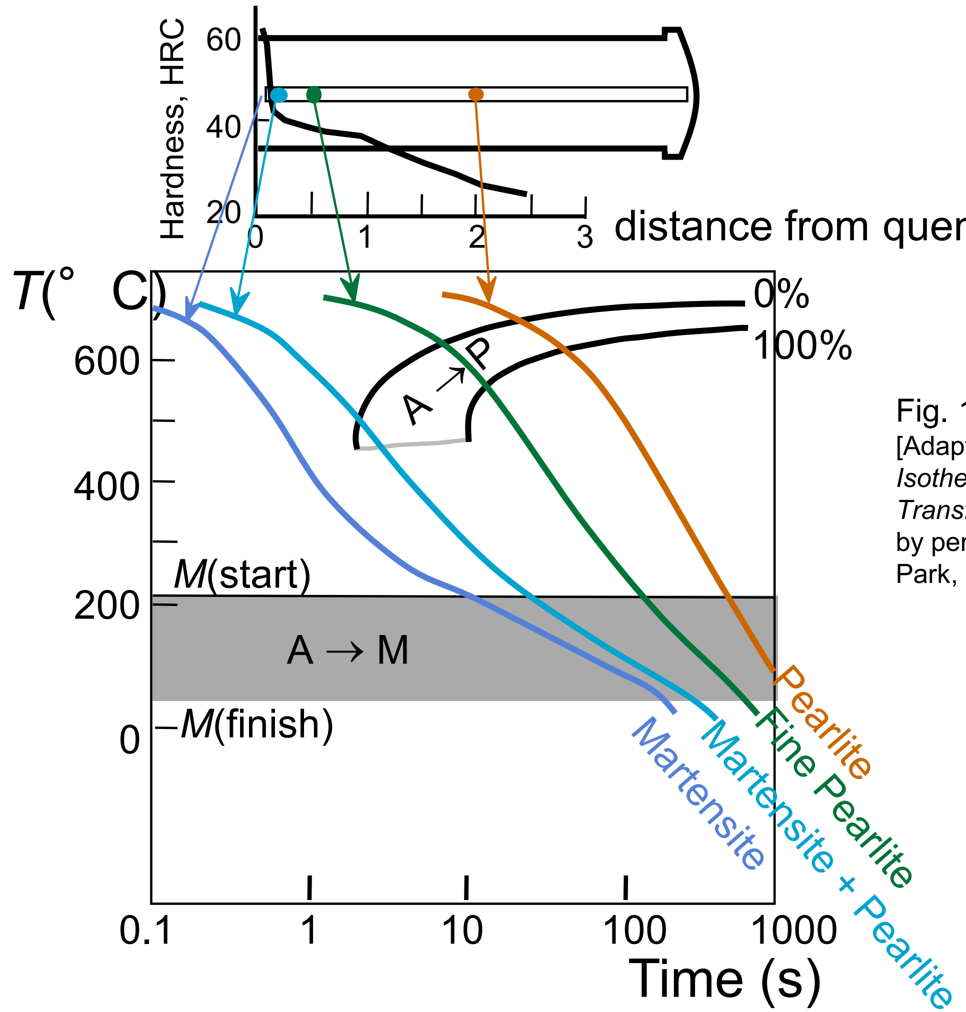
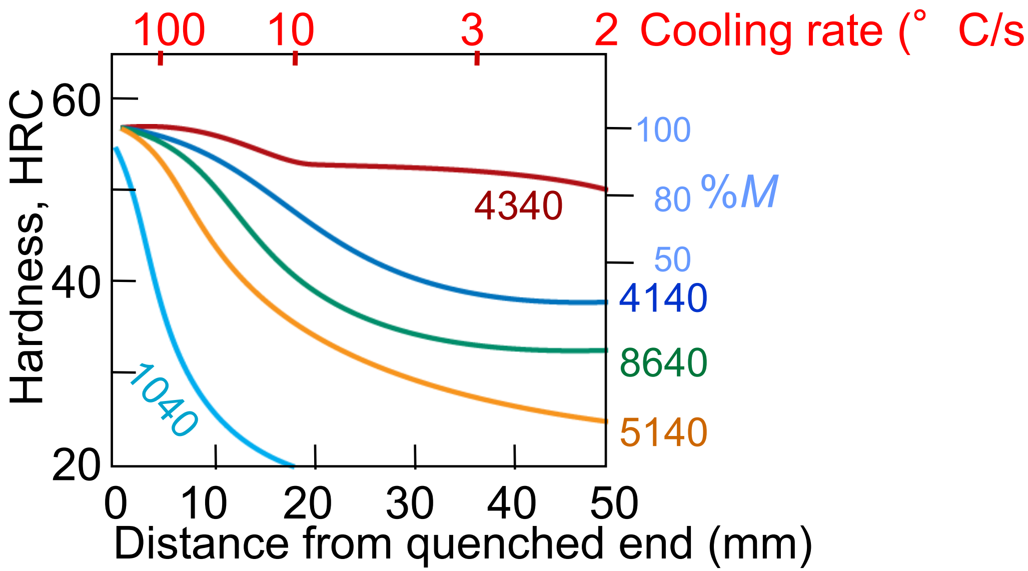


Fig. 11.17, *Callister & Rethwisch 10e*. [Adapted from H. Boyer (Ed.), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977. Reproduced by permission of ASM International, Materials Park, OH.]

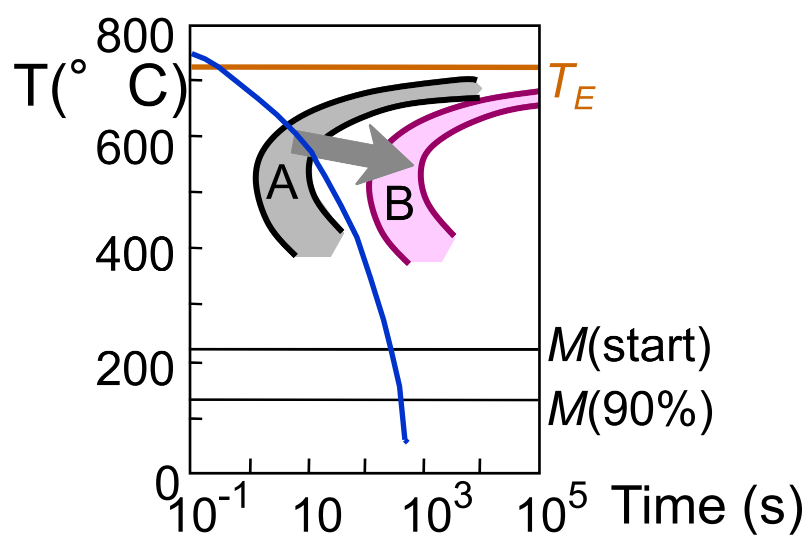
Hardenability vs Alloy Composition

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

Fig. 11.18, *Callister & Rethwisch 10e*.
(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:

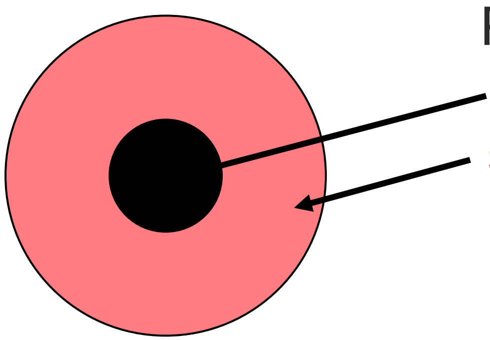
Medium	Severity of Quench	Hardness
air	low	low
oil	moderate	moderate
water	high	high

- 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