CHAPTER

9

Engineering Alloys

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Production of Iron and Steel

- **Production of pig iron**

$$\underbrace{\underbrace{Fe_2O_3}_{\text{Ore}} + \underbrace{3CO}_{\text{Coke}}}_{\text{Blast Furnace}} \longrightarrow \underbrace{2Fe}_{\text{Pig iron (Liquid)}} + 3CO_2$$

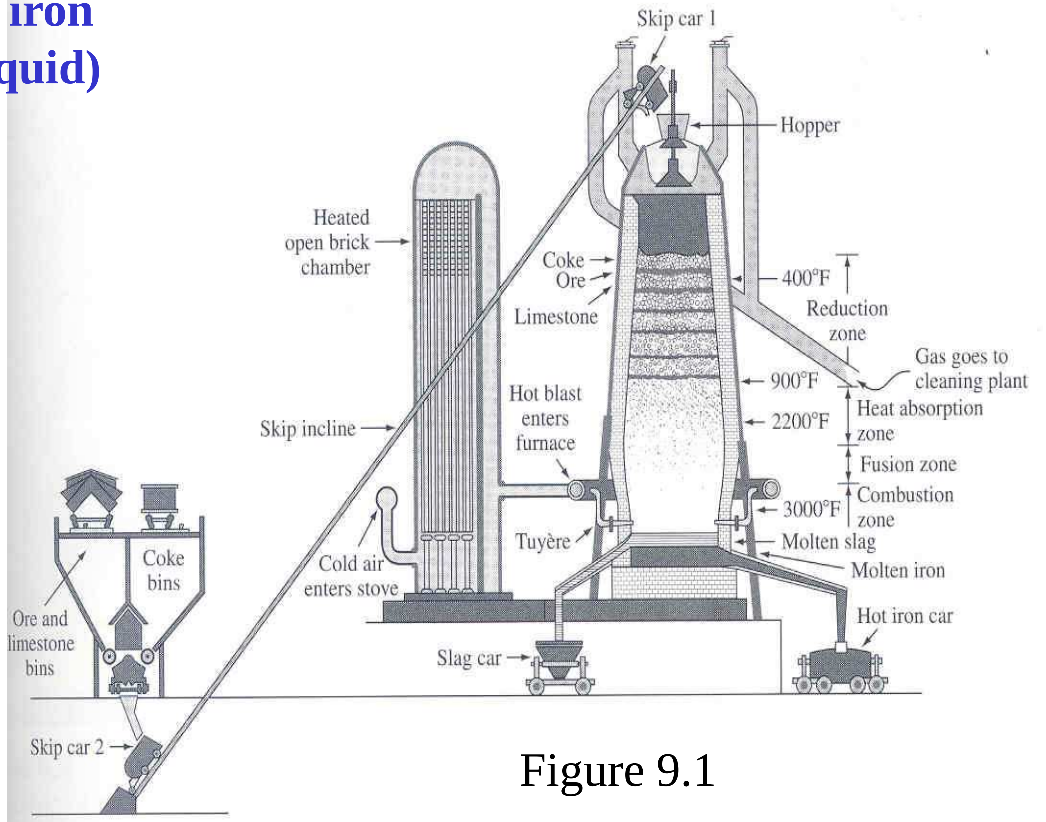

Figure 9.1

After A. G. Guy,"Elements of Physical Metallurgy,"2nd ed., !959, Addision-Wesley, Fig. 2-5, p.21.

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Steel Making

- Pig iron and 30% steel crap is fed into refractory furnace to which oxygen lane is inserted.
- Oxygen reacts with liquid bath to form iron oxide.
- $FeO + C \rightarrow Fe + CO$
- Slag forming fluxes are added.
- Carbon content and other impurities are lowered.
- Molten steel is continuously cast and formed into shapes.

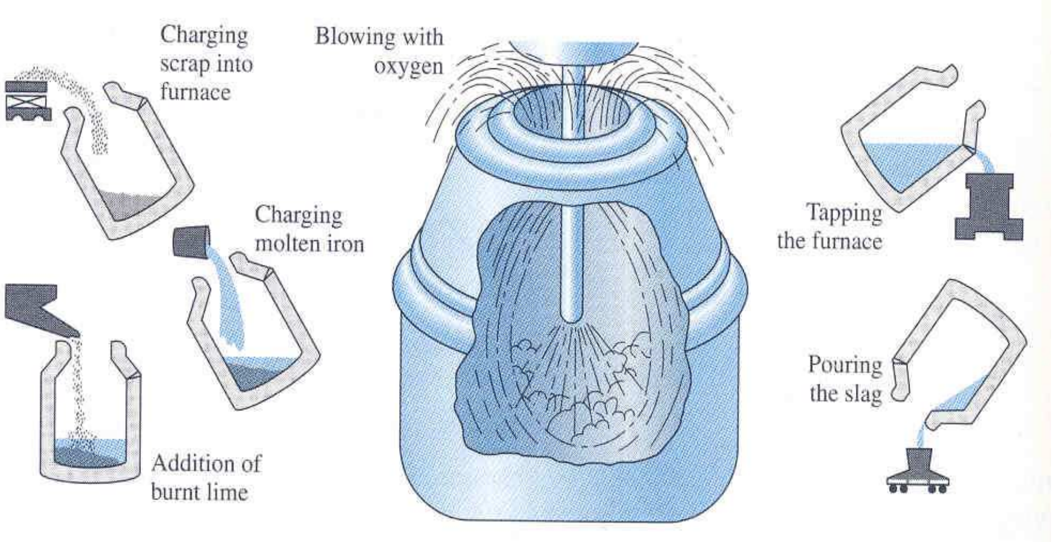

Figure 9.2

Courtesy of Inland Steel

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Iron Carbide Phase Diagram

- **Plain carbon steel** ⟶ **0.03% to 1.2% C, 0.25 to 1% Mn and other impurities.**
- **α Ferrite: Very low solubility of carbon. Max 0.02 % at 723^{0}C and 0.005% at 0^{0}C.**
- **Austenite: Interstitial solid solution of carbon in γ iron. Solubility of C is 2.08% at 1148^{0}C and 0.8% at 0^{0}C.**
- **Cementite: Intermetallic compound. 6.67% C and 93.3% Fe.**

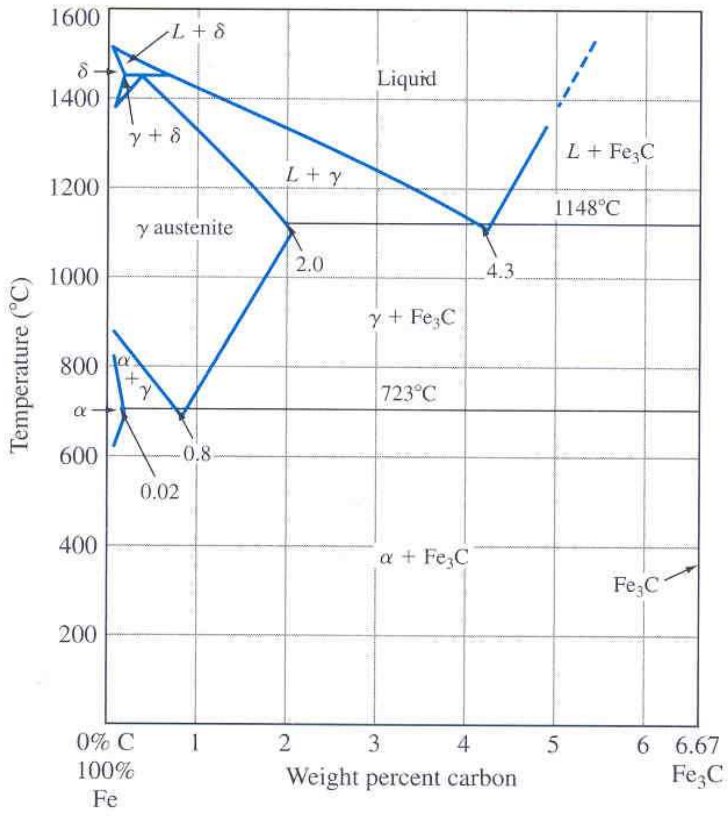

Figure 9.6

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Invariant reactions

- **Peritectic reaction:**

$$\text{Liquid (0.53\%C)} + \delta\ \text{(0.09\% C)} \xrightarrow{1495^{0}\text{C}} \gamma\ \text{(0.17\% C)}$$

- **Eutectic reaction:**

$$\text{Liquid (4.3\% C)} \xrightarrow{1148^{0}\text{C}} \gamma\ \text{austenite (2.08\%C)} + Fe_3C\ \text{(6.67\%C)}$$

- **Eutectoid reaction:**

$$\gamma\ \text{Austenite (0.8\%C)} \xrightarrow{723^{0}\text{C}} \alpha\ \text{Ferrite(0.02\%C)} + Fe_3C\ \text{(6.67\%C)}$$

$$\text{Hypoeutectoid Steel} \xleftarrow{\text{Less than 0.8\%}} \text{0.8\% C Eutectoid Steel} \xrightarrow{\text{More than 0.8\%}} \text{Hypereutectoid Steel}$$

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Slow Cooling of Plain Carbon Steel

- **Eutectoid plain carbon steel:** **If a sample is heated up to 750^{0}C and held for sufficient time, structure will become homogeneous austenite.**

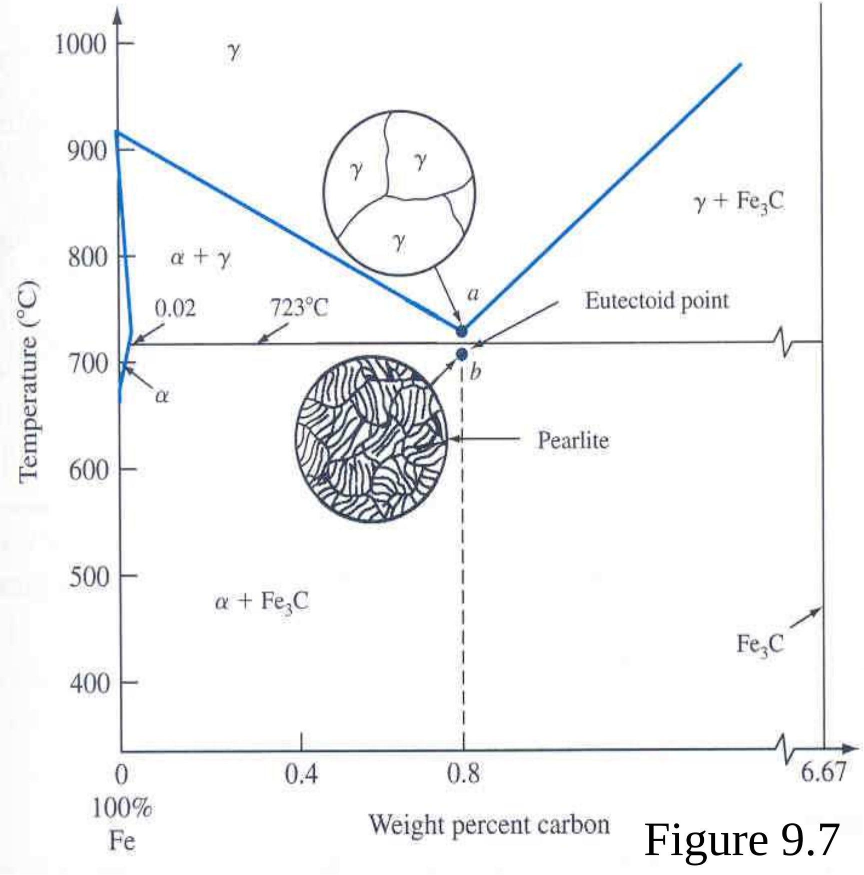

Figure 9.7

- **Below eutectoid temperature, layers of ferrite and cementite are formed.** ⇨ **Pearlite.**

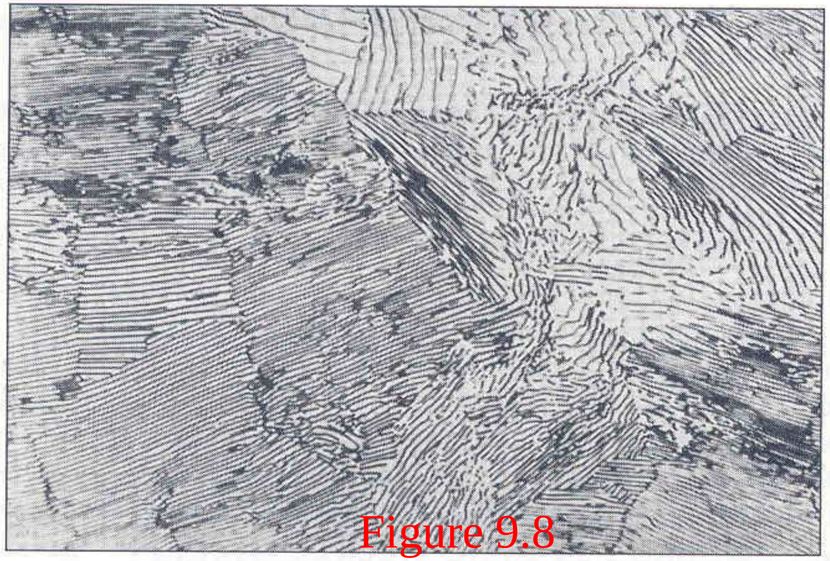

Figure 9.8

After W. F. Smith, “The Structure and Properties of Engineering Alloys,” 2nd ed.,McGraw-Hill, 1981, p.8

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Slow Cooling of Plain Carbon Steel (Cont..)

- **Hypoeutectoid plain carbon steel: If a sample of 0.4% C is heated up to 900^{0}C, it gets austenitized.**
- **Further cooling gives rise to α and pearlite.**

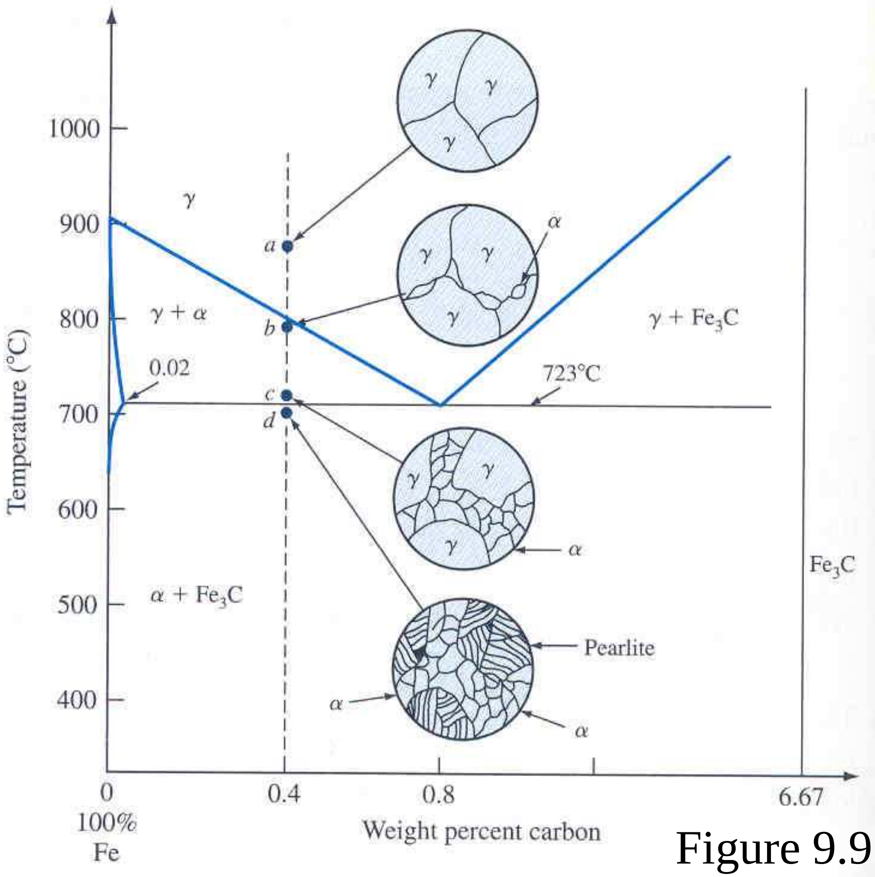

Figure 9.9

Pearlite

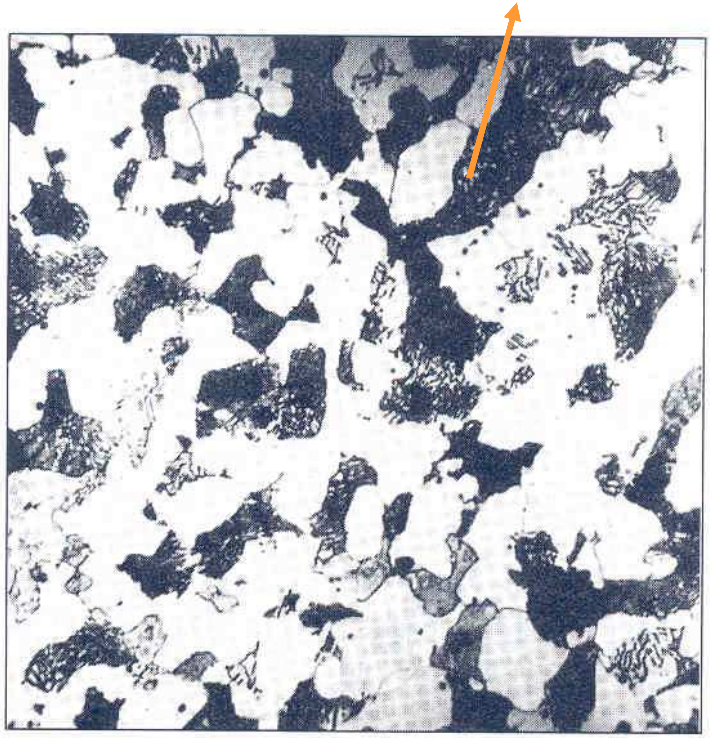

Figure 9.10

After W. F. Smith, “The Structure and Properties of Engineering Alloys,” 2nd ed.,McGraw-Hill, 1981, p.10

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Slow Cooling of Plain Carbon Steel (Cont..)

- **Hypereutectoid plain carbon steel:** **If a 1.2% C sample is heated up to 950^{0}C and held for sufficient time, it entirely gets austenitized.**
- **Further cooling results results in eutectoid cementite and pearlite.**

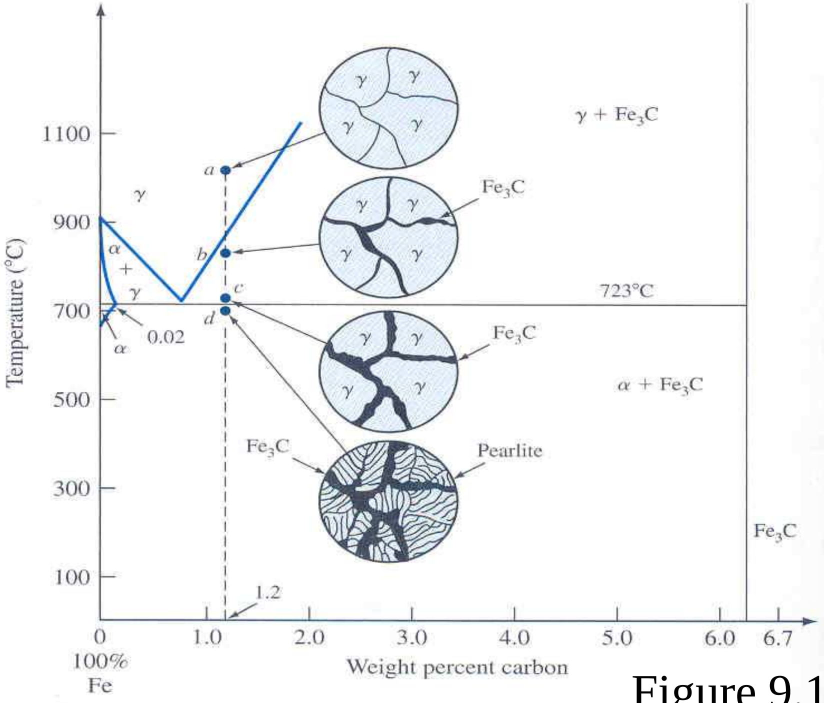

Figure 9.11

After W. F. Smith, "The Structure and Properties of Engineering Alloys," 2nd ed.,McGraw-Hill, 1981, p.12.

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Heat treatment of plain carbon steels.

- **Heating and cooling properties of steels vary mechanical properties.**
- **Martensite: Metastable phase consisting of super saturated solid solution of C in BCC or BCC tetragonal iron.**
- **Caused by rapid cooling of austenitic steel into room temperature (quenching).**

Ms ⟶ temperature of martensite start.

Mf ⟶ temperature of martensite finish.

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Microstructure of Fe – C Martensites

- **Lath martensite:** **Less than 0.6% C and consists of domains of lathe of different orientation.**
- **Plate martensite:** **More than 0.6% C and have fine structure of parallel twins.**

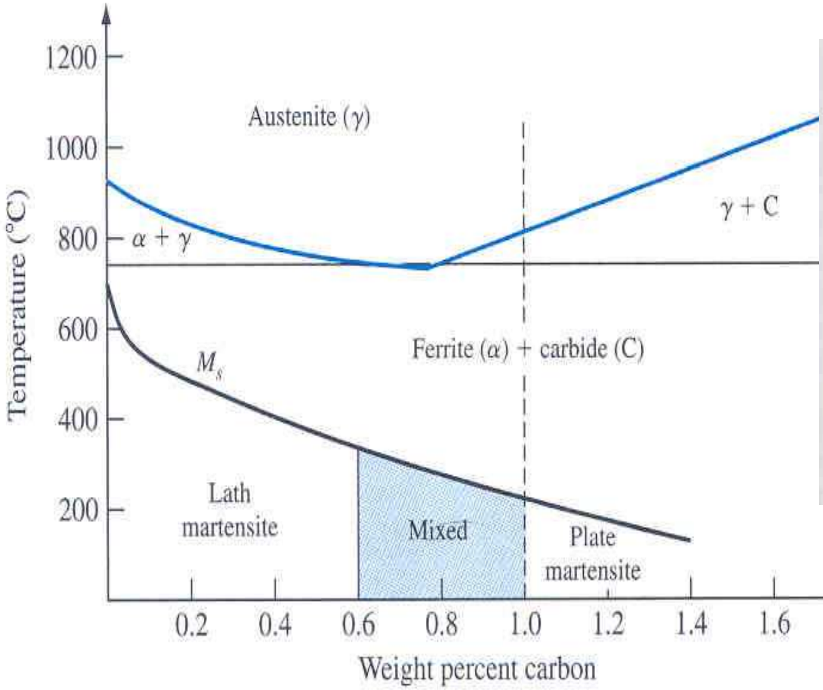
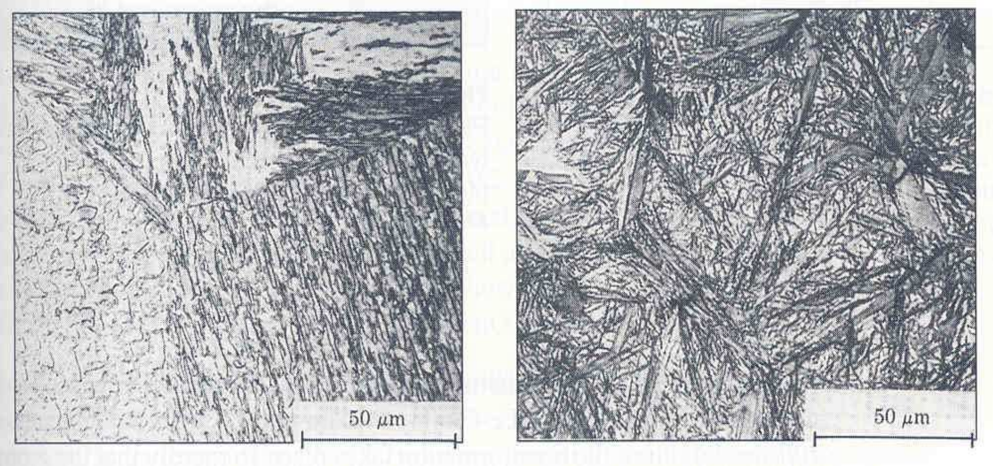


Figure 9.13



Lath type **Plate type**

Figure 9.14

After A. R. Marder and G. Krauss, as presented in “Hardenebility Concepts with Applications to Steel,” AIME, 1978, p. 238.

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Martensite (Cont..)

- Transfer to martensite is diffusionless.
- No change of relative position of carbon atoms after transformation.

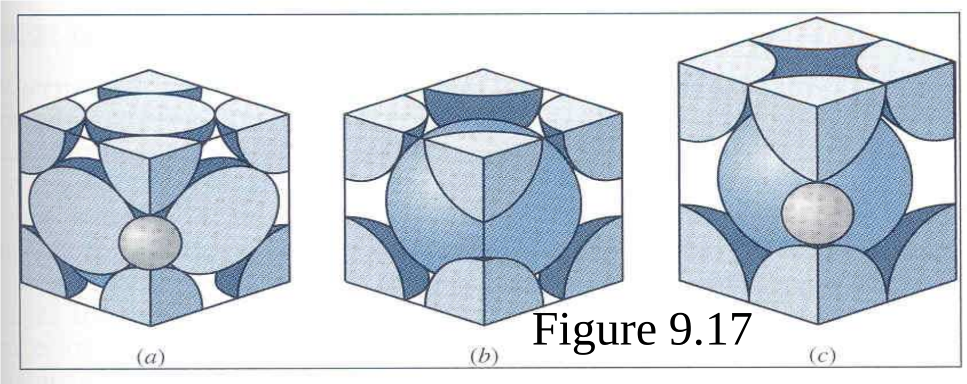

Figure 9.17

- Strength and hardness increases with carbon content.
- Strength is due to high dislocation concentration and interstitial solid solution strengthening.

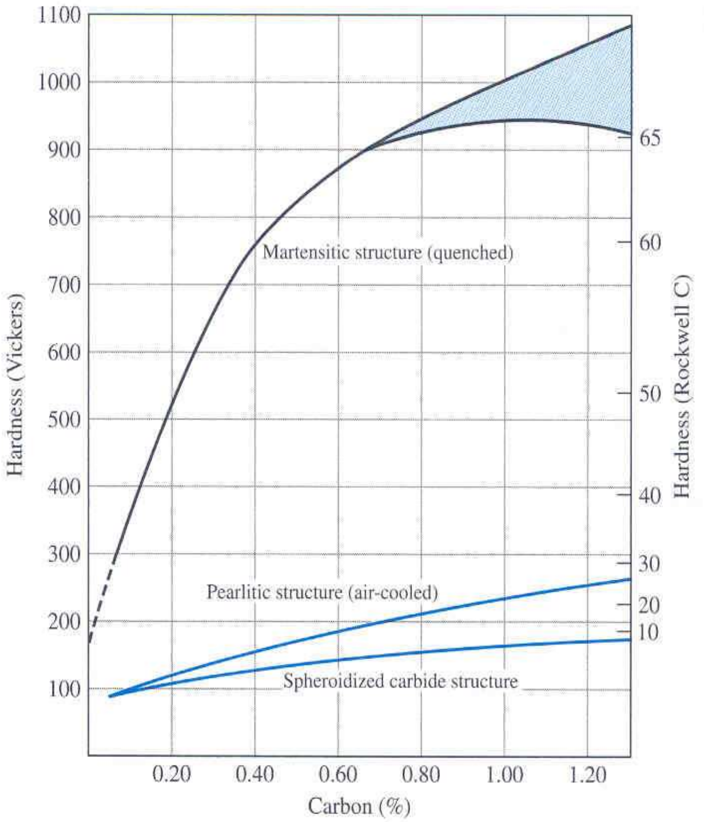

Figure 9.19

After E. R. Parker and V. F. Zackay Strong and Ductile Steels, Sci.Am.,November 1968, p.36; Copyright by Scientific American, Inc; all rights reserved

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Isothermal decomposition of Austenite.

- **Several samples are first austenitized above eutectoid temperature and rapidly cooled in sand bath to desired temperature in a salt bath and then quenched in water at various time intervals.**

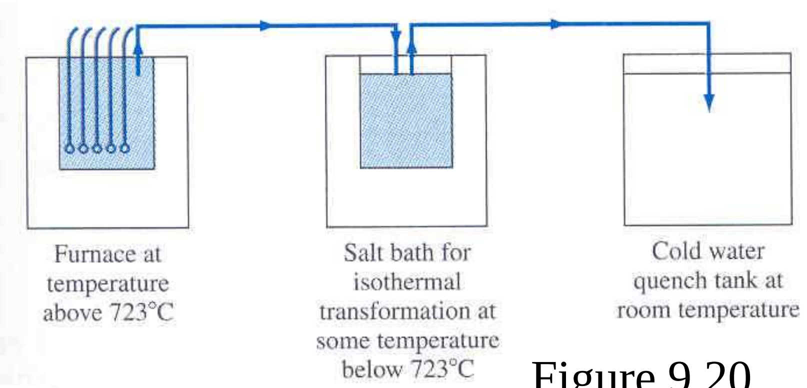

Figure 9.20

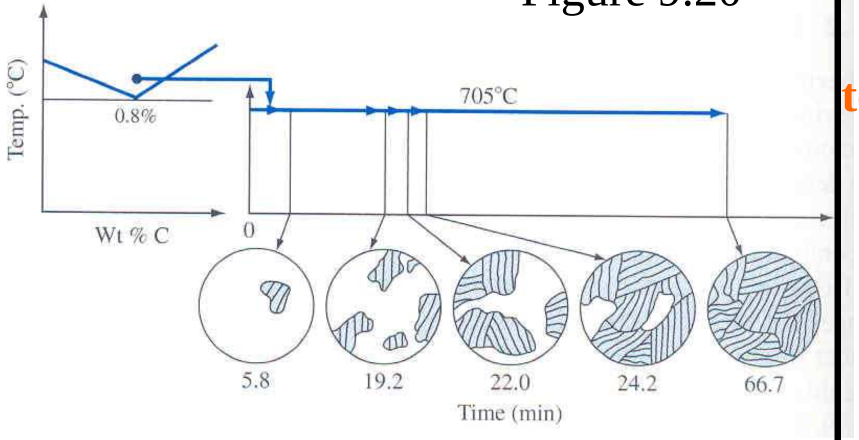

Figure 9.21

Repeat procedure at

progressive lower temperatures

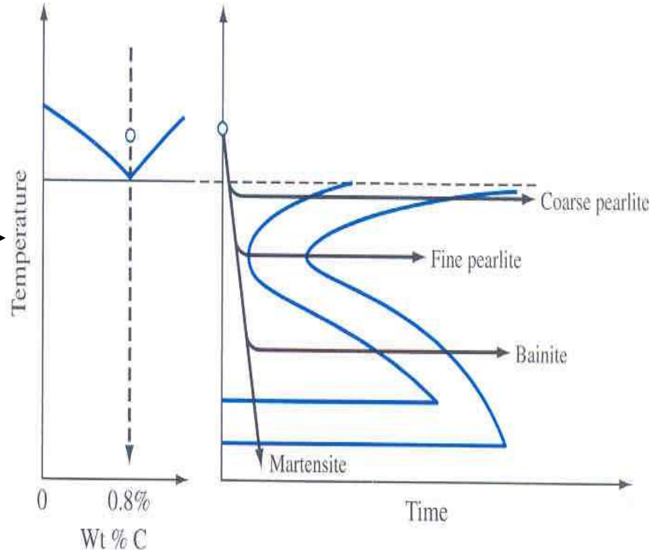

Figure 9.22

After W. F. Smith, "The Structure and Properties of Engineering Alloys," McGraw-Hill, 1981, p.14

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Isothermal decomposition of Austenite (Cont..)

- **If hot quenching temperature is between 550^{0}C to 250^{0}C, an intermediate structure Bainite is produced.**
- **Bainite contain nonlamellar eutectoid structure of α ferrite and cementite.**
- **Upper Bainite ⟶ Between 550^{0}C and 350^{0}C**
- **Lower Bainite ⟶ Between 350^{0}C and 250^{0}C**

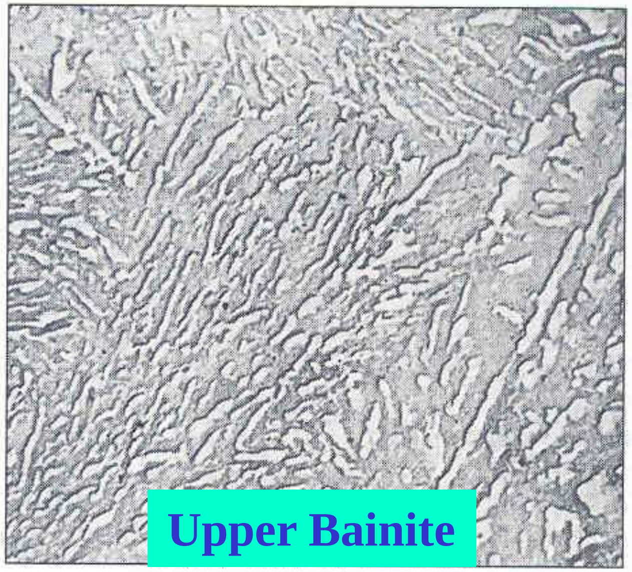

Figure 9.24

After H. E. McGannon(ed.), "The Making Shaping and Treating of Steel," 9th ed., United States Steel Corp., 1971

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IT Diagrams for Noneutectoid Steels

- **‘S’ curves of IT diagrams of noneutectoid steel is shifted to left.**
- **Not possible to quench from austenitic region to produce entirely martensite.**
- **Additional transformation line indicates start and formation of proeutectoid ferrite.**

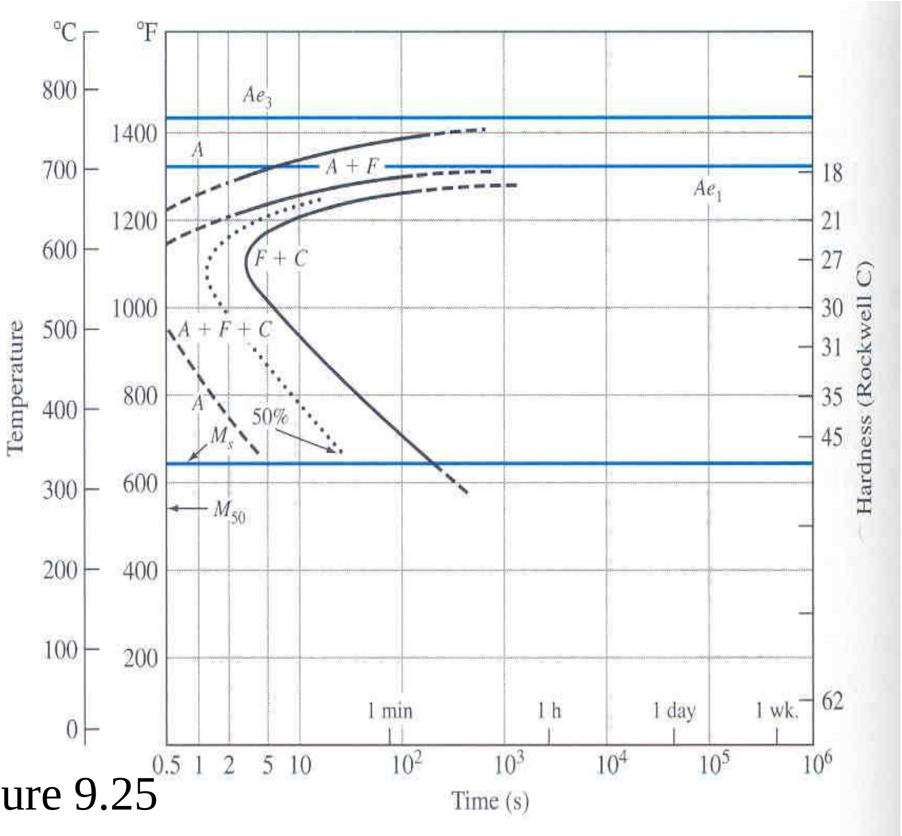

Figure 9.25

After R. A. Grange, V. E. Lambert, and J. J. Harrington, Trans, ASM, 51:377(1959)

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Continuous Cooling-Transformation Diagram

- **In continuous cooling transformation from martensite to pearlite takes place at a range of temperature.**
- **Start and finish lines shifted to longer time.**
- **No transformation below 450^{0}C.**

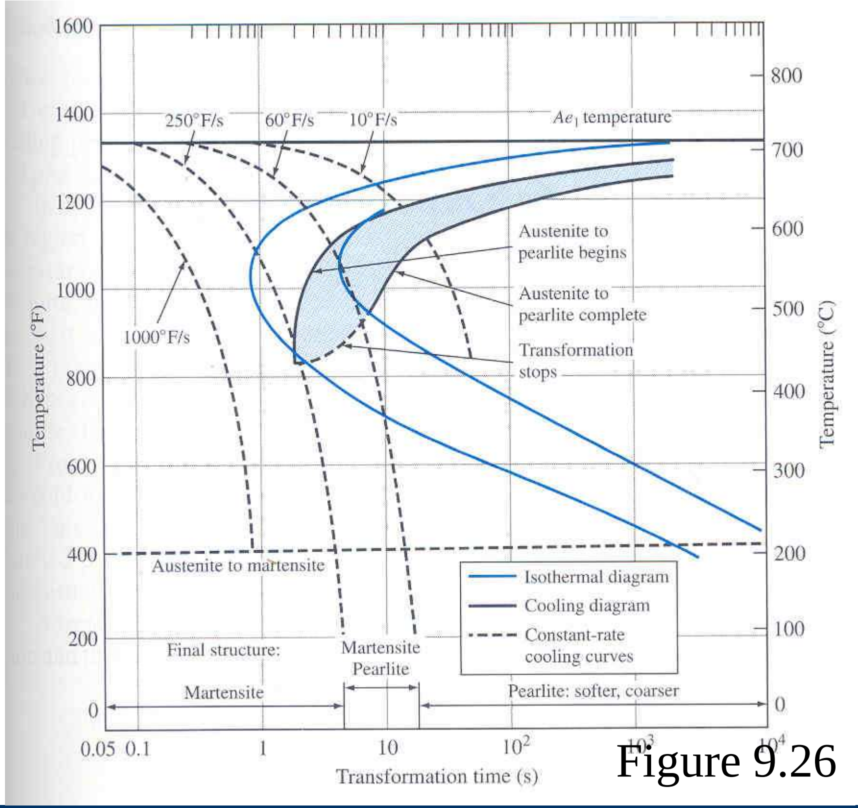

Figure 9.26

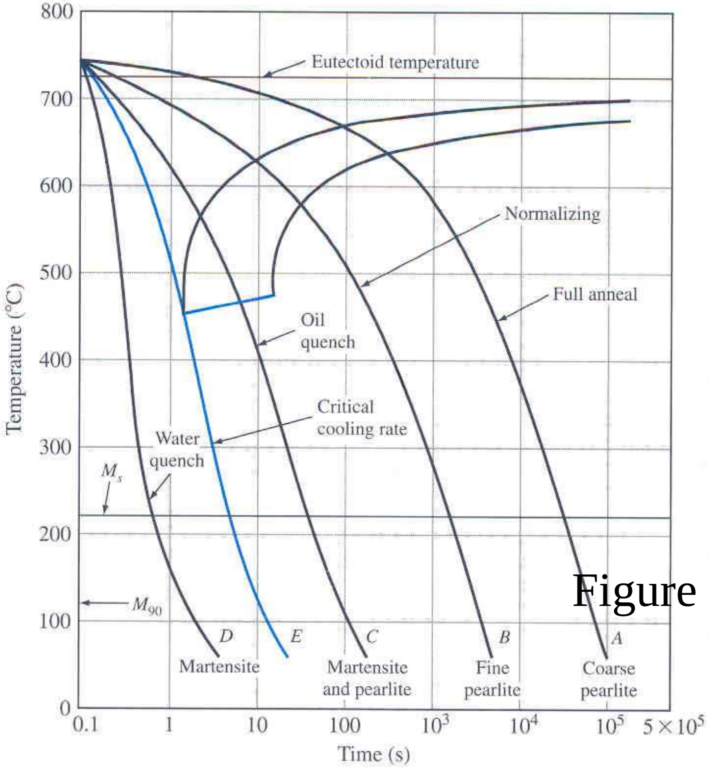

Figure 9.27

After R. A. Grange and J. M. Kiefer, "Alloying Elements in Steel," ASM 2nd ed., 1966, p.254.

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Annealing and Normalizing

- **Full annealing:** **Sample heated to 40^0C above austenite ferrite boundary, held for necessary time and cooled slowly.**
- **Process annealing:** **Used for stress relief. Applied to hypoeutectoid steel at eutectoid temperature.**
- **Normalizing:** **Steel heated in austenite region and cooled in still air.**
- **Makes grain structure uniform**
- **Increases strength**

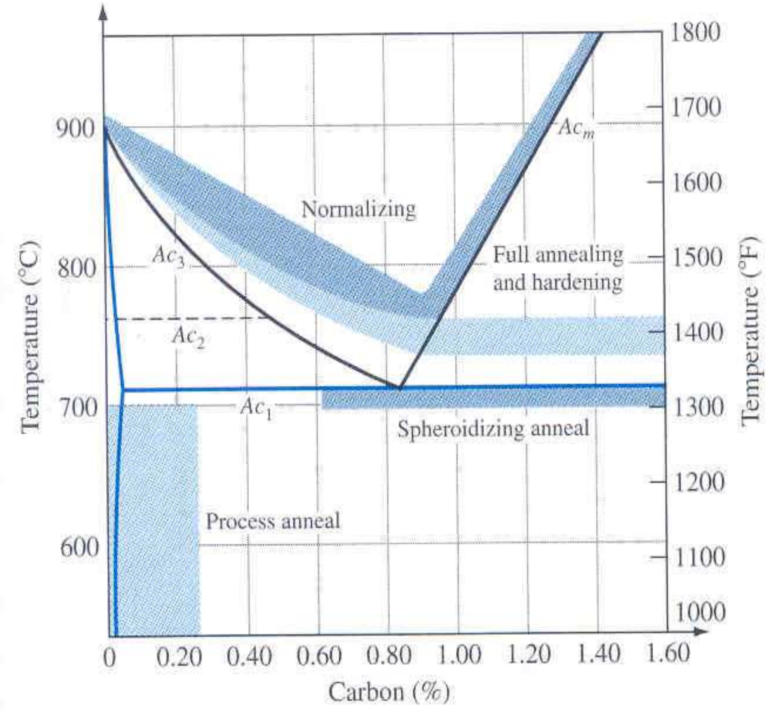

Figure 9.28

After T. G. Diggers et al., " Heat Treatment and Properties of Iron and Steel," NBS Monograph 88, 1966, p. 10

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Tempering of Plain Carbon Steel

- **Martensitic steel is heated at a temperature below eutectic temperature.**
- **Makes steel softer and ductile.**
- **Carbon atoms, in low carbon steels, segregate themselves on tempering.**

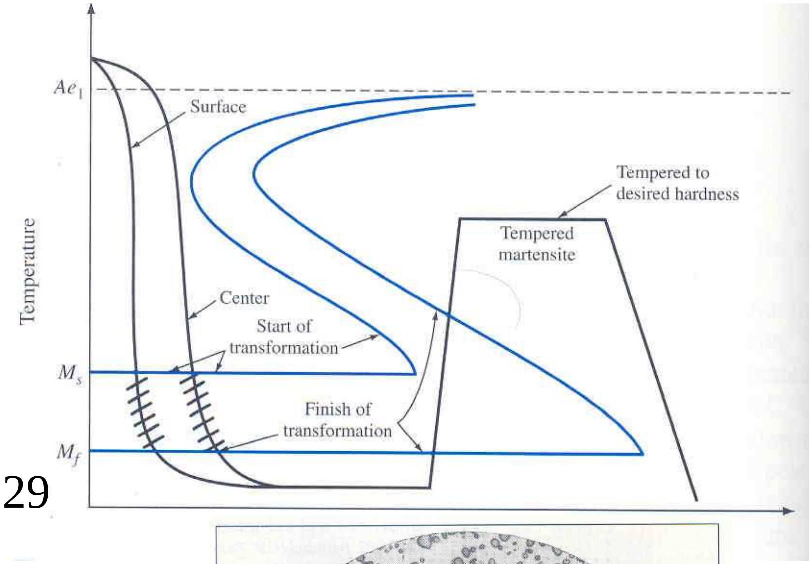

Figure 9.29

Tempering Temperature	**Structure**
Below 2000C	**Epsilon Carbide**
200 – 700^{0}C	**Cementite (rod-like)**
400 – 700^{0}C	**Cementite (Spheroidite)**

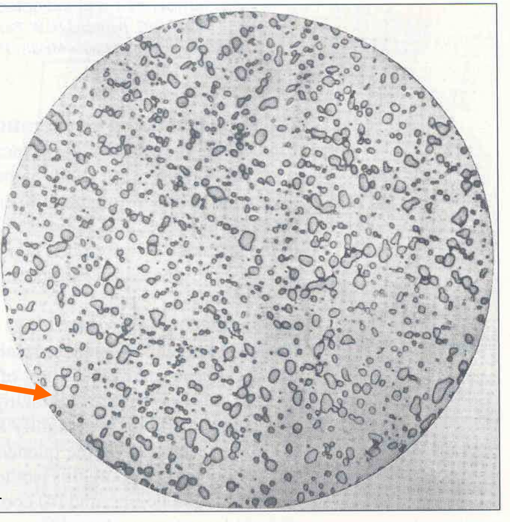

Figure 9.31

From " Suiting the heat Treatment to the job," United States Steel Corp., 1968, p.34.

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Effects of Tempering

- **Hardness decreases as temperature increases above 200^0C**
- **This is due to diffusion of carbon atoms from interstitial sites to iron carbide precipitates.**

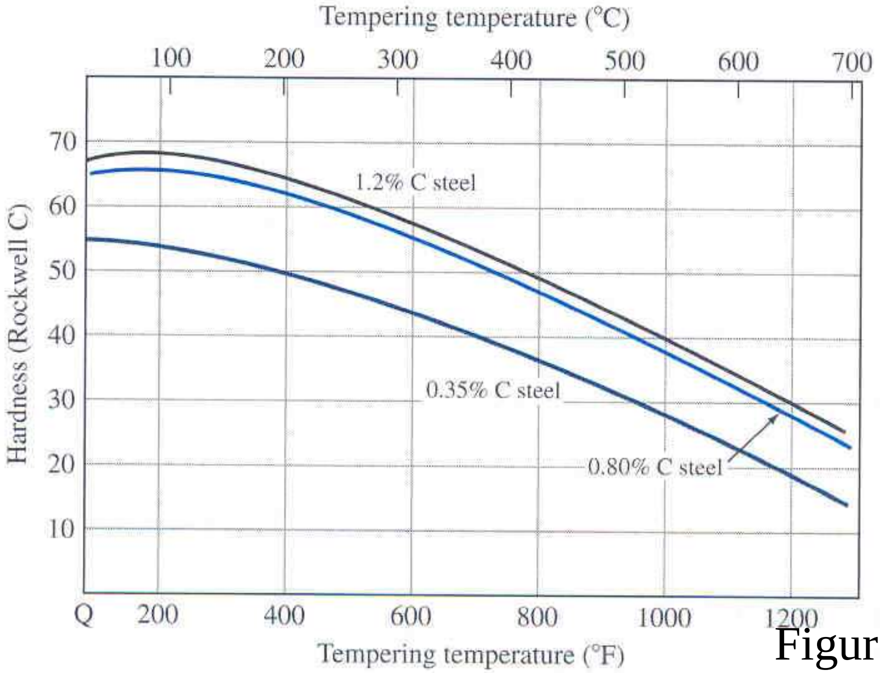

Figure 9.32

After JE. C. Bain, and H. W. Paxton, "Alloying Elements in Steel, " 2^{nd} ed., American Society for Metals, 1996 p.38.

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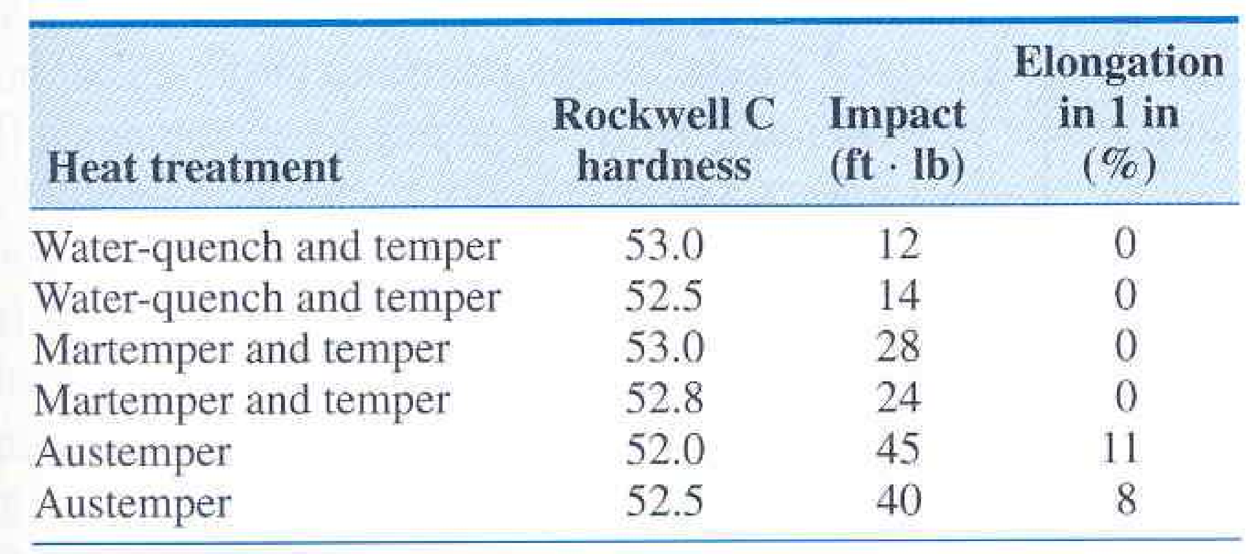
Martempering and Austempering

- **Martempering (Marquenching): Austinitizing, quenching at around Ms, holding in quenching media until temperature is uniform, removing before Bainite forms and cooling at a moderate rate.**
- **Austempering: Same as martempering but held at quenching media till austenite to Bainite transformation takes place.**

Table 9.2



Heat treatment	Rockwell C hardness	Impact (ft · lb)	Elongation in 1 in (%)
Water-quench and temper	53.0	12	0
Water-quench and temper	52.5	14	0
Martemper and temper	53.0	28	0
Martemper and temper	52.8	24	0
Austemper	52.0	45	11
Austemper	52.5	40	8

Source: "Metals Handbook," vol. 2, 8th ed., American Society for Metals, 1964.

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Calssification of Plain Carbon Steel

- **Four digit AISI-SAE code.**
- **First two digits, 10, indicate plain carbon steel.**
- **Last two digits indicate carbon content in 100th wt%.**
- **Example: 1030 steel indicate plain carbon steel containing 0.30 wt% carbon.**
- **As carbon content increase, steel becomes stronger and ductile.**

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Low Alloy Steels

- **Limitations of plain carbon steels:**
  - **Cannot be strengthened beyond 690 MPa without loosing ductility and impact strength.**
  - **Not deep hardenable.**
  - **Low corrosion resistance**
  - **Rapid quenching leads to crack and distortion.**
  - **Poor impact resistance at low temperature.**

- **Alloy steels: Up to 50% alloying elements like manganese, nickel, chromium, molybdenum and tungsten.**

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Classification of Alloy Steels

- **First two digits:** **Principle alloying element.**
- **Last two digits:** **% of carbon.**

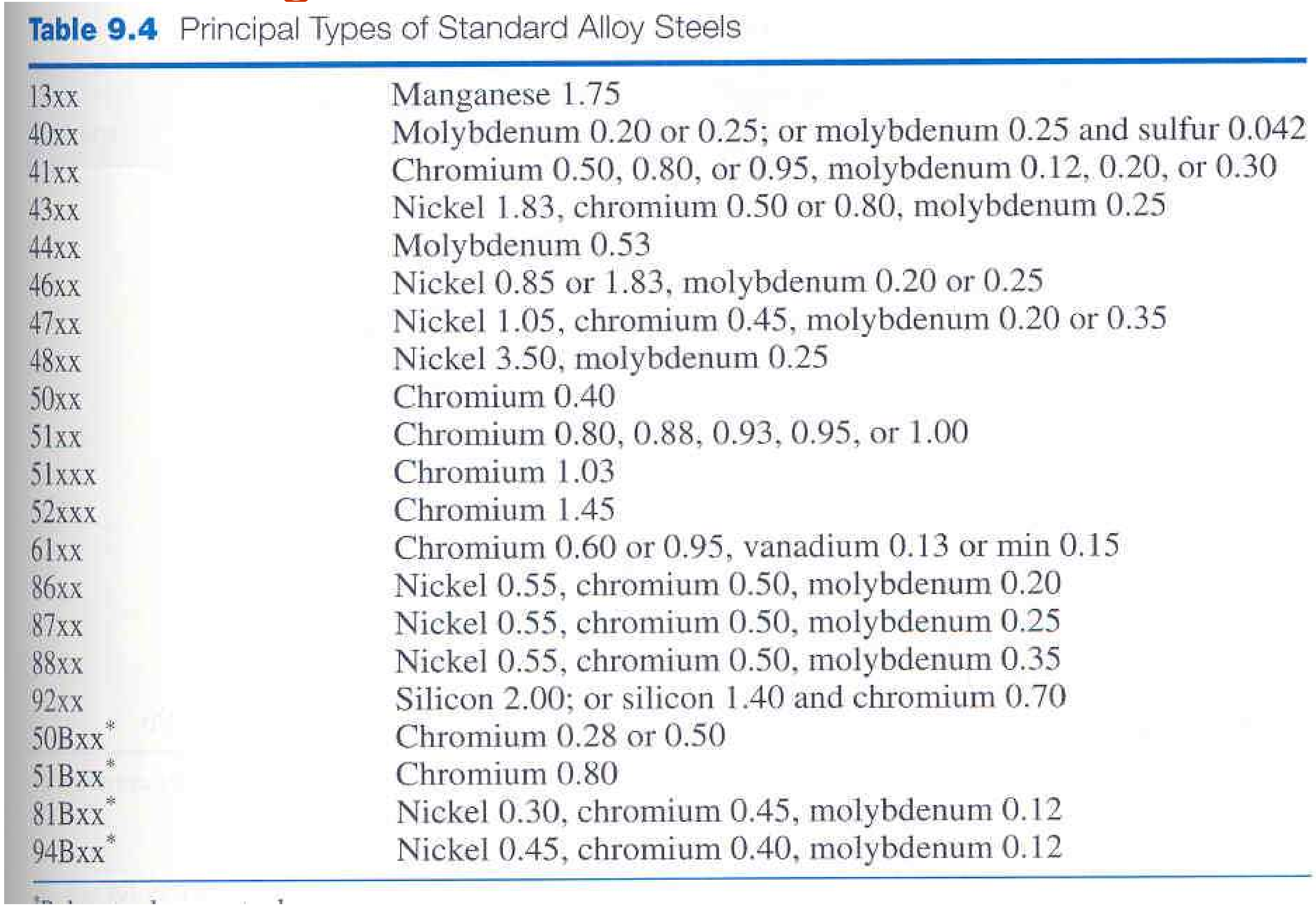

Table 9.4 Principal Types of Standard Alloy Steels

13xx	Manganese 1.75
40xx	Molybdenum 0.20 or 0.25; or molybdenum 0.25 and sulfur 0.042
41xx	Chromium 0.50, 0.80, or 0.95, molybdenum 0.12, 0.20, or 0.30
43xx	Nickel 1.83, chromium 0.50 or 0.80, molybdenum 0.25
44xx	Molybdenum 0.53
46xx	Nickel 0.85 or 1.83, molybdenum 0.20 or 0.25
47xx	Nickel 1.05, chromium 0.45, molybdenum 0.20 or 0.35
48xx	Nickel 3.50, molybdenum 0.25
50xx	Chromium 0.40
51xx	Chromium 0.80, 0.88, 0.93, 0.95, or 1.00
51xxx	Chromium 1.03
52xxx	Chromium 1.45
61xx	Chromium 0.60 or 0.95, vanadium 0.13 or min 0.15
86xx	Nickel 0.55, chromium 0.50, molybdenum 0.20
87xx	Nickel 0.55, chromium 0.50, molybdenum 0.25
88xx	Nickel 0.55, chromium 0.50, molybdenum 0.35
92xx	Silicon 2.00; or silicon 1.40 and chromium 0.70
50Bxx*	Chromium 0.28 or 0.50
51Bxx*	Chromium 0.80
81Bxx*	Nickel 0.30, chromium 0.45, molybdenum 0.12
94Bxx*	Nickel 0.45, chromium 0.40, molybdenum 0.12

Source: “Alooy Steel: Semifinished; Hot-Rolled and Cold-Finished Bars,” American Iron and Steel Institute, 1970.

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Distribution of Alloying Elements

- **Distribution depends upon compound and carbide forming tendency of each element.**

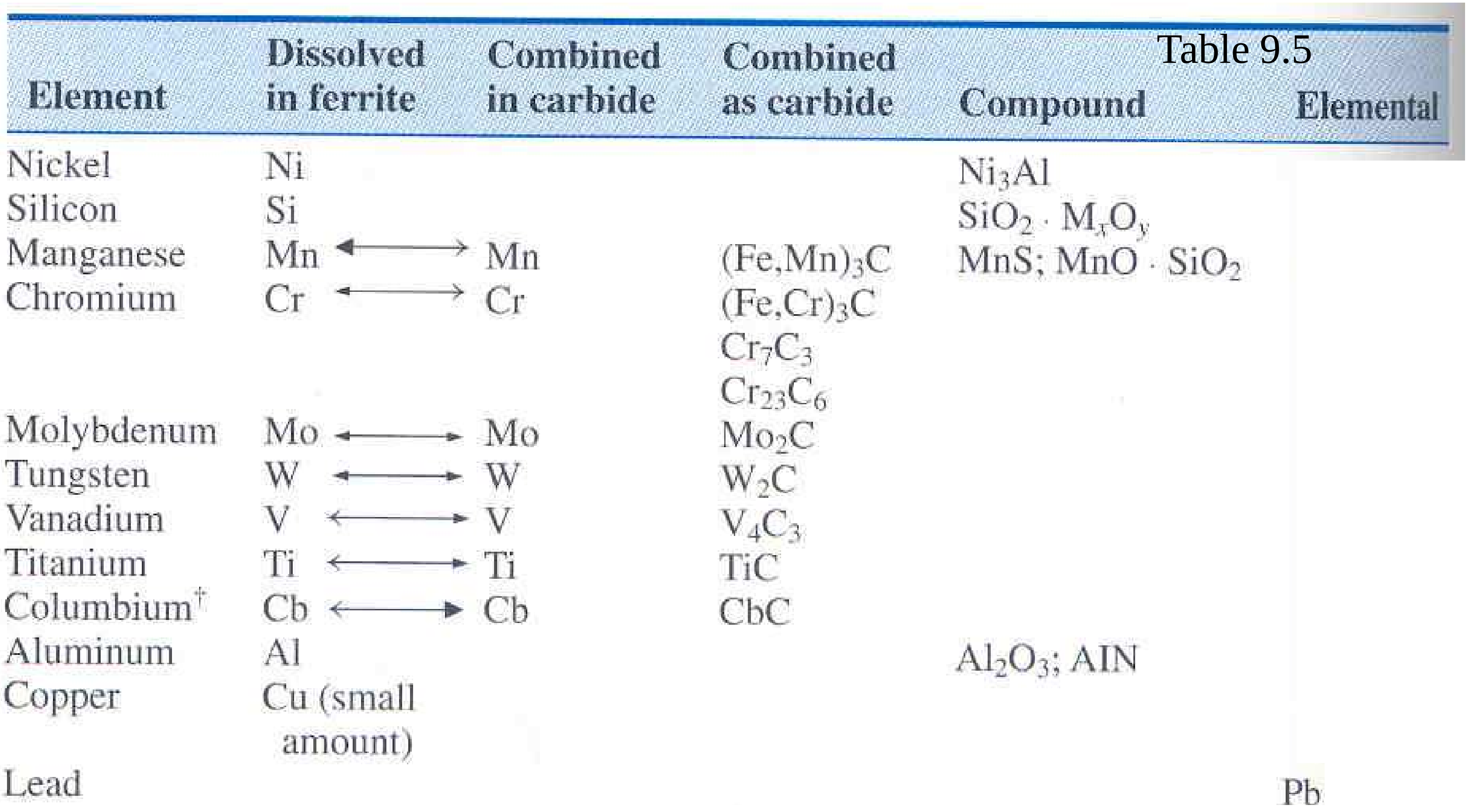

Table 9.5

Element	Dissolved in ferrite		Combined in carbide	Combined as carbide	Compound	Elemental
Nickel	Ni				Ni_3Al	
Silicon	Si				$SiO_2 \cdot M_xO_y$	
Manganese	Mn	⟷	Mn	$(Fe,Mn)_3C$	MnS; $MnO \cdot SiO_2$	
Chromium	Cr	⟷	Cr	$(Fe,Cr)_3C$ Cr_7C_3 $Cr_{23}C_6$		
Molybdenum	Mo	⟷	Mo	Mo_2C		
Tungsten	W	⟷	W	W_2C		
Vanadium	V	⟷	V	V_4C_3		
Titanium	Ti	⟷	Ti	TiC		
Columbium[†]	Cb	⟷	Cb	CbC		
Aluminum	Al				Al_2O_3; AIN	
Copper	Cu (small amount)					
Lead						Pb

After JE. C. Bain, and H. W. Paxton, “Alloying Elements in Steel, “ 2nd ed., American Society for Metals, 1996

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Effects of Alloying Element on Eutectoid Temperature

- **Mn and Ni lower eutectoid temperature.**
- **They act as austenite stabilizing element.**
- **Tungsten, molybdenum and titanium raise eutectic temperature.**
- **They are called ferrite stabilizing elements.**

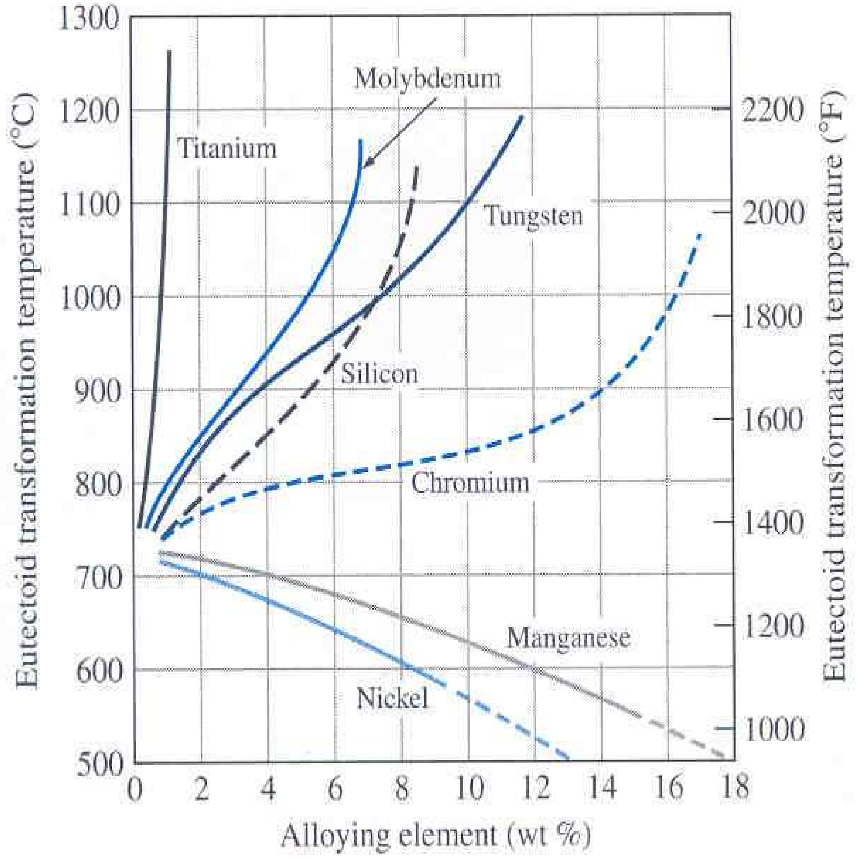

Figure 9.35

Source: "Metals Handbook," vol. 2, 9th ed., American Society for Metals, 1973.

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Hardenability

- **Hardenability determines the depth and distribution of hardness induced by quenching.**
- **Hardenability depends on**
  - **Composition**
  - **Austenitic grain size**
  - **Structure before quenching**
- **Joming hardenability test:**
- **Cylindrical bar (1 inch dia and 4 inch length with 1/16 in flange at one end is austenitized and one end is quenched.**
- **Rockwell C hardness is measured up to 2.5 inch from quenched end.**

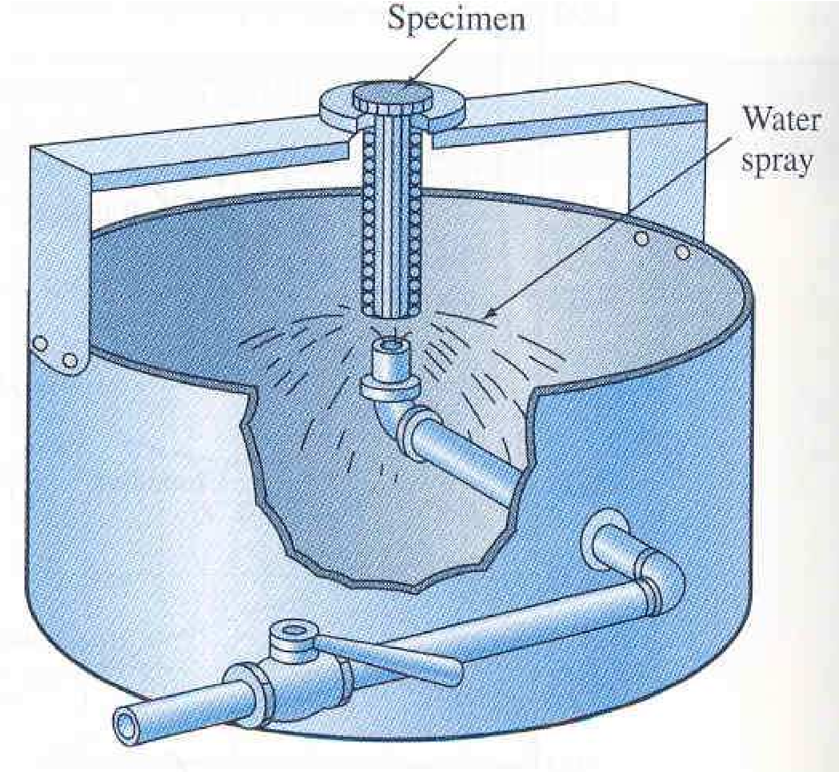

Figure 9.36b

After H. E. McGannon(ed.), “The Making Shaping and Treating of Steel,” 9th ed., United States Steel Corp., 1971, p.1099

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Hardenability (cont..)

- **For 1080 plain carbon steel, the hardness value at quenched end is 65 HRC while it is 50 HRC at 3/16 inch from quenched end.**
- **Alloy steel 4340 has high hardenability and has hardness of 40 HRC 2 inches from quenched end.**
- **In alloy steel, decomposition of austenite to ferrite is delayed.**
- **Cooling rate depends on bar dia, quenching media and bar cross section.**

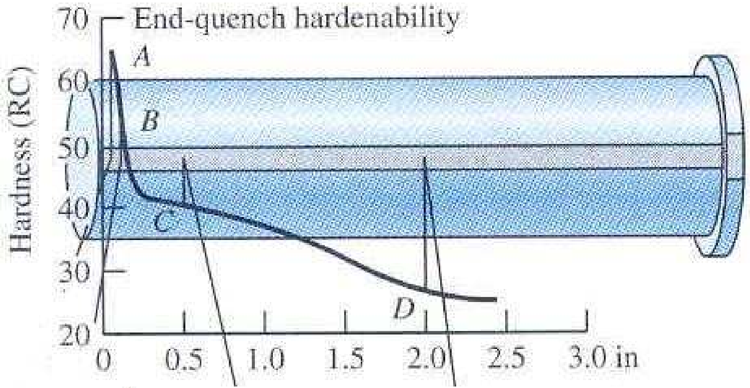

Figure 9.37

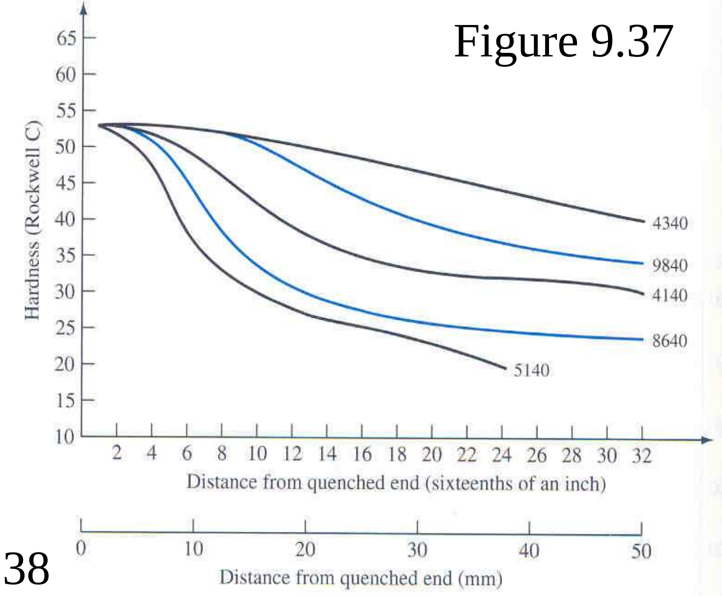

Figure 9.38

After H. E. McGannon(ed.), “The Making Shaping and Treating of Steel,” United States Steel Corp., 1971, p.1139.

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Mechanical Properties of Low Alloy Steels

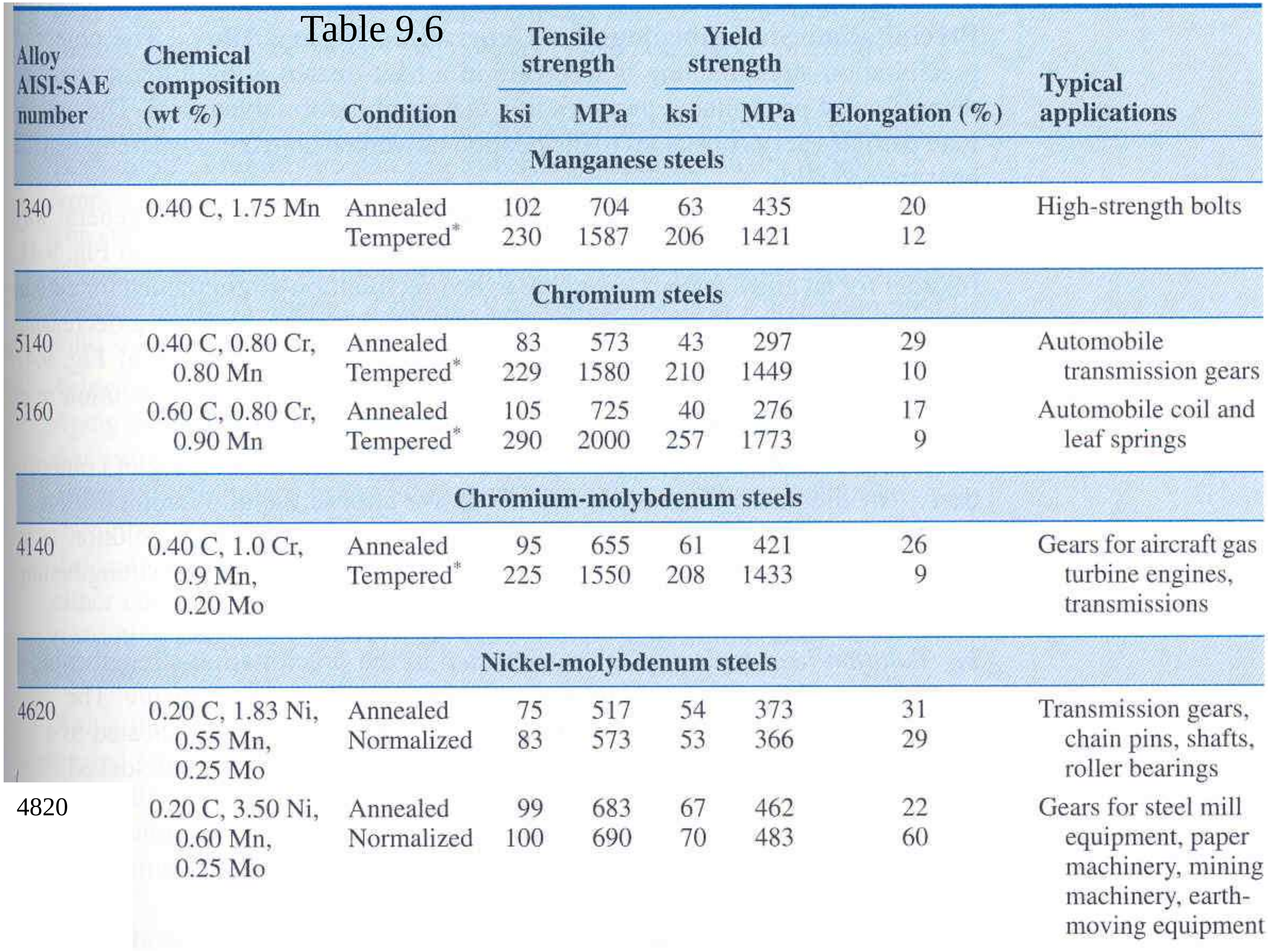

Table 9.6

Alloy AISI-SAE number	Chemical composition (wt %)	Condition	Tensile strength ksi	Tensile strength MPa	Yield strength ksi	Yield strength MPa	Elongation (%)	Typical applications
Manganese steels								
1340	0.40 C, 1.75 Mn	Annealed Tempered*	102 230	704 1587	63 206	435 1421	20 12	High-strength bolts
Chromium steels								
5140	0.40 C, 0.80 Cr, 0.80 Mn	Annealed Tempered*	83 229	573 1580	43 210	297 1449	29 10	Automobile transmission gears
5160	0.60 C, 0.80 Cr, 0.90 Mn	Annealed Tempered*	105 290	725 2000	40 257	276 1773	17 9	Automobile coil and leaf springs
Chromium-molybdenum steels								
4140	0.40 C, 1.0 Cr, 0.9 Mn, 0.20 Mo	Annealed Tempered*	95 225	655 1550	61 208	421 1433	26 9	Gears for aircraft gas turbine engines, transmissions
Nickel-molybdenum steels								
4620	0.20 C, 1.83 Ni, 0.55 Mn, 0.25 Mo	Annealed Normalized	75 83	517 573	54 53	373 366	31 29	Transmission gears, chain pins, shafts, roller bearings
4820	0.20 C, 3.50 Ni, 0.60 Mn, 0.25 Mo	Annealed Normalized	99 100	683 690	67 70	462 483	22 60	Gears for steel mill equipment, paper machinery, mining machinery, earth-moving equipment

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Aluminum Alloys

- **Precipitation Strengthening : Creates fine dispersion of precipitated particles in the metal and hinder dislocation movement.**
- **Basic steps :**
  - **Solution heat treatment: Alloy sample heated to a temperature between solvus and solidus and soaked at that temperature.**
  - **Quenching: Sample then quenched to room temperature in water.**
  - **Aging: Solutionized and quenched sample is then aged to form finely dispersed particles.**

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Decomposition Products Created by Aging

- **Super saturated solid solution is in unstable condition.**
- **Alloy tends to seek a lower energy state by decomposing into metastable or equilibrium phase.**
- **Supersaturated solid solution as highest energy state.**
- **Equilibrium precipitate has lowest energy state.**

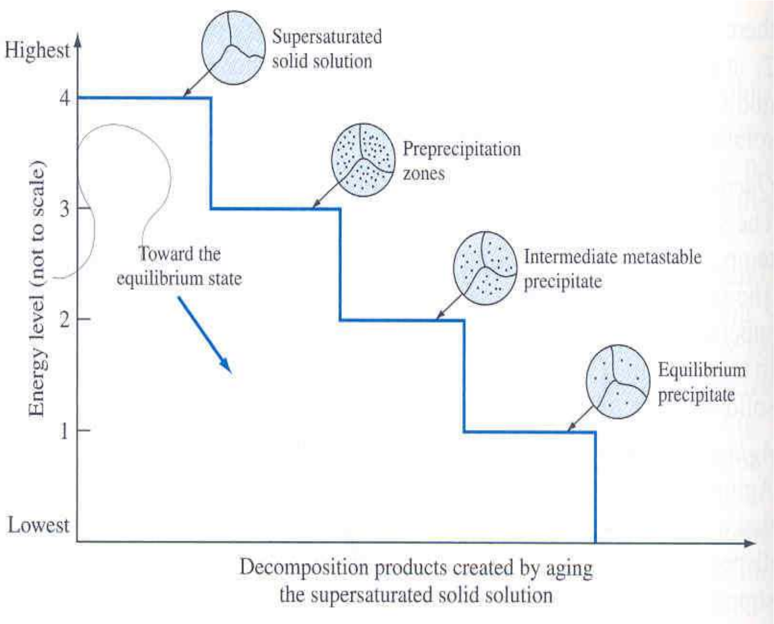

Figure 9.42

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Effects of Aging on Strength

- **Aging curve:** **Plot of strength or hardness versus aging time.**
- **As aging time increases alloy becomes stronger harder and less ductile.**
- **Overaging decreases strength and hardness.**

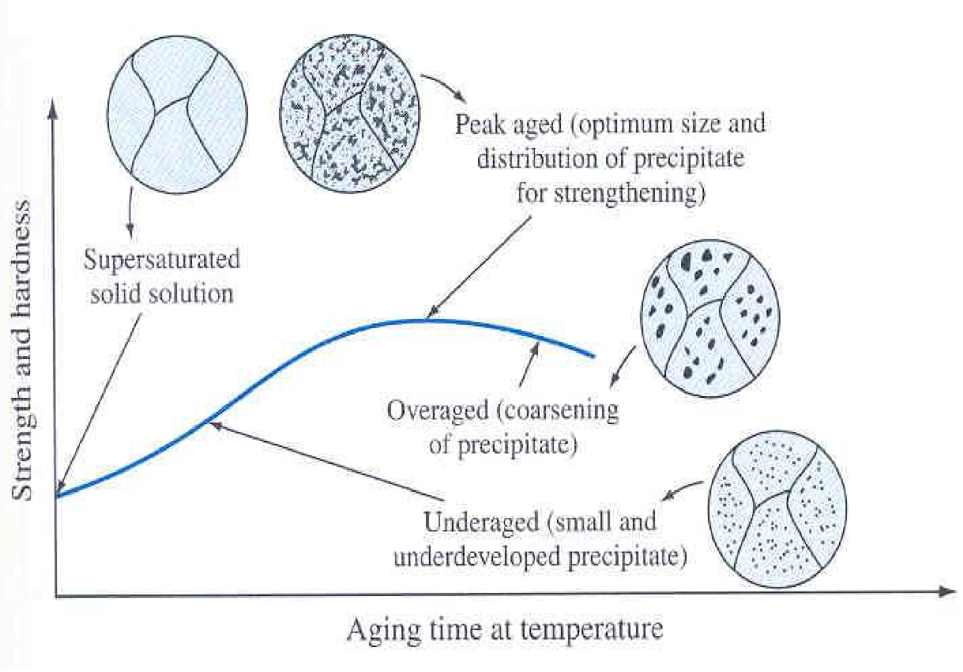

Figure 9.43

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Example - Al 4% Cu Alloy

- **Al -4% Cu is solutionized at about 515^{0}C**
- **Alloy is rapidly cooled in water.**
- **Alloy is artificially aged in 130 – 190^{0}C**
- **Structures formed :**
  - **GP1 Zone: At lower aging temperature, copper atom is segregated in supersaturated solid solution.**
  - **GP2 Zone: Tetragonal structure, 10-100 nm diameter.**
  - **θ’ Phase: Nucleates heterogeneously on dislocation.**
  - **θ Phase: Equilibrium phase, incoherent ($CuAl_2$).**

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Correlation of Structure and Hardness

- **GP1 and GP2 Zones increases hardness by stopping dislocation movement.**
- **At 130^{0}C when θ' forms, hardness is maximum.**
- **After θ' forms, GP2 zones are dissolved and θ' gets coarsened reducing hardness.**

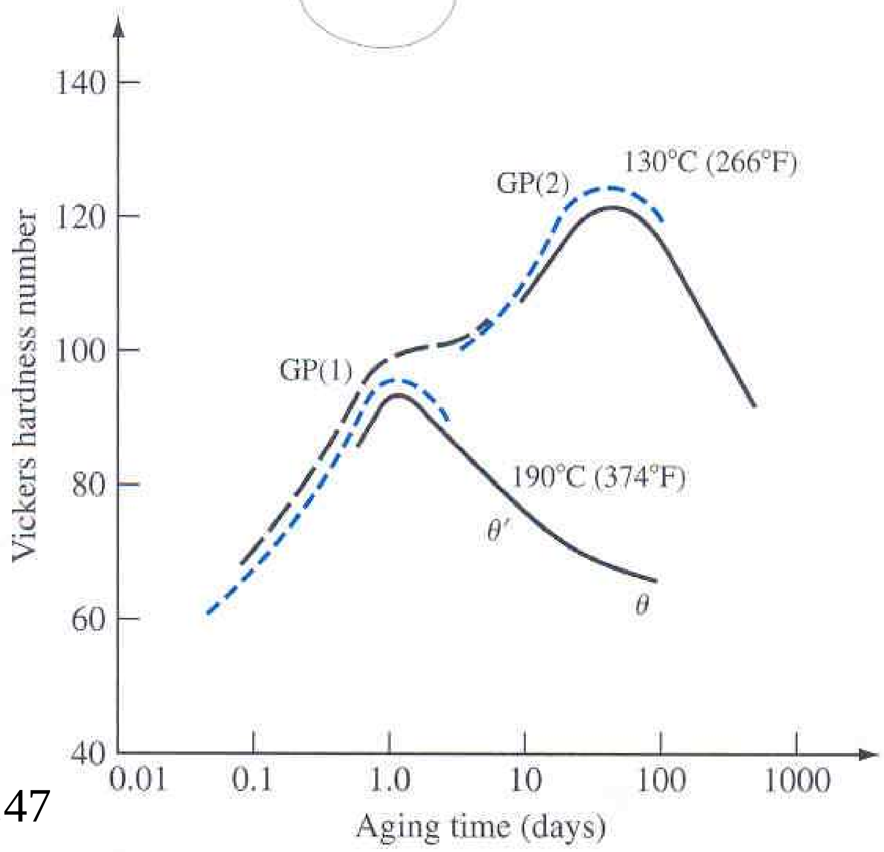

Figure 9.47

After J. M. Silcock, T. J. Heal, and H. K. Hardy “Alluminium,” 1, American society of Metals, 1967,p.123.

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General Properties of Aluminum

- **Low density, corrosion resistance.**
- **High alloy strength (about 690 MPa)**
- **Nontoxic and good electrical properties.**
- **Production:** **Aluminum Ore (Bauxite)** + **Hot NaOH** → **Sodium Aluminate**
- **Aluminum hydroxide is precipitated from aluminum solution.**
- **Aluminum hydroxide is thickened and calcined to Al_2O_3 which is dissolve in cryolite and electrolyzed.**

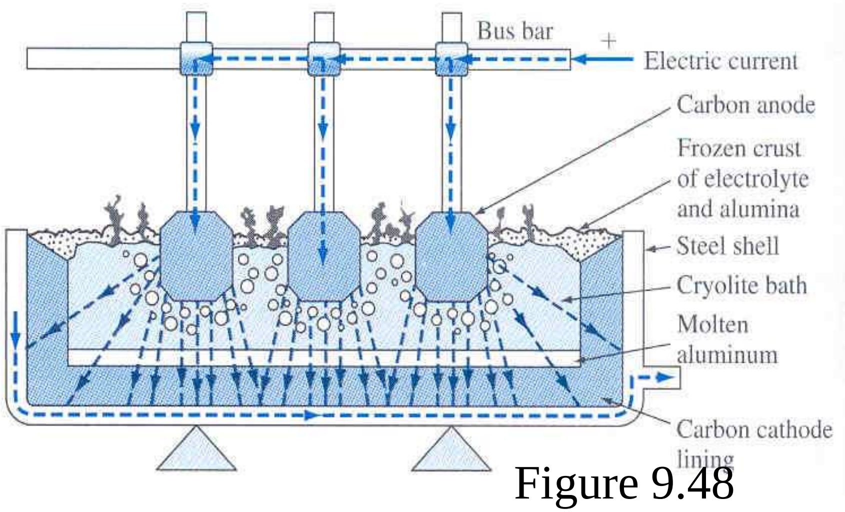

Figure 9.48

- **Metallic aluminum sinks to bottom and is tapped out.**

Courtesy of Aluminium Company of America

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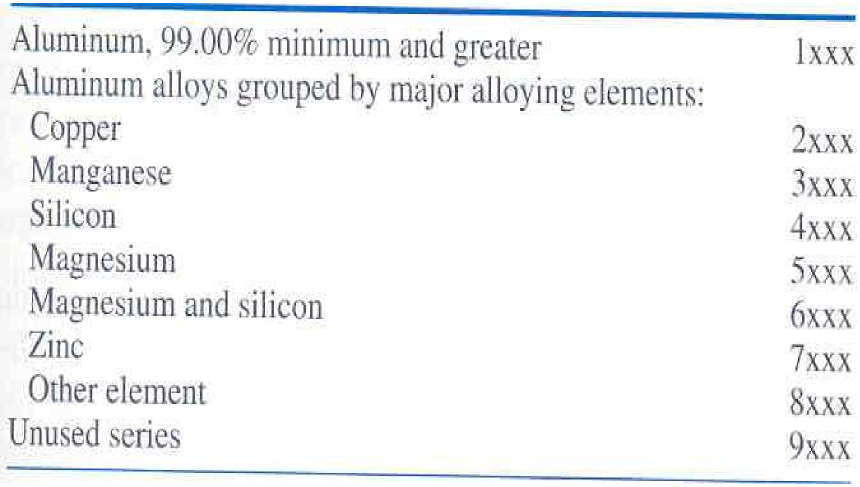
Wrought Aluminum Alloys

- **Primary Fabrication:** **Usually semiconsciously cast by direct chill method.**
- **Scalping:** **½ inch metal is removed from hot rolled surface for good finishing.**
- **Ingots are homogenized and rolled.**
- **Classification:** **According to major alloying elements.**
- **Four digits:** **First digit - major group of alloying elements.**
- **Second digit:** **Impurity limits.**
- **Last 2 digits:** **Identify aluminum alloy.**

Table 9.7



Aluminum, 99.00% minimum and greater	1xxx
Aluminum alloys grouped by major alloying elements:	
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium and silicon	6xxx
Zinc	7xxx
Other element	8xxx
Unused series	9xxx

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Temper Designations

- **Temper designations are designated by hyphen.**
- **Example: 2024-T6**

F – as fabricated
O – Annealed
H – Strain hardened.
T – Heat treated to produce stable temper

H1 – Strain hardened alloy.
H2 – Strain hardened and partially annealed.
H3 - Strain hardened an annealed

T1 – Naturally aged
T3 – Solution heat treated.
T4 – Solution heat treated and naturally aged.
T5 - Cooled and artificially aged.
T6 - Solution heat treated and artificially aged.
T7 - Solution heat treated and stabilized.
T8 - Solution heat treated, cold worked and then artificially aged.

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Non Heat Treatable Aluminum Alloys

- **1xxx alloys : 99% Al + Fe + Si + 0.12% Cu**

  Tensile strength = 90 MPa

  Used for sheet metals

- **3xxx alloys : Manganese is principle alloying element.**

  Al 3003 = Al 1100 + 1.25% Mn

  Tensile strength = 110 MPa

  General purpose alloy

- **5xxx alloys: Al + up to 5% Mg**

  Al5052 = Al + 25%Mg + 0.2% Cr

  Tensile strength = 193 MPa

  Used in bus, truck and marine sheet metals.

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Heat Treatable Aluminum Alloys

- **2xxx alloys : Al + Cu + Mg**

  Al2024 = Al + 4.5% Cu + 1.5% Mg +0.6%Mn

  Strength = 442 MPa

  Used for aircraft structures.

- **6xxx alloys: Al + Mg + Si**

  Al6061 = Al + 1% Mg + 0.6%Si + 0.3% Cu + 0.2% Cr

  Strength = 290 MPa

  Used for general purpose structure.

- **7xxx alloys: A + Zn + Mg + Cu**

  Al7075 = Al + 5.6% Zn + 2.5% Mg + 1.6% Cu + 0.25% Cr

  Strength = 504 MPa

  Used for aircraft structures.

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Aluminum Casting

- **Sand Casting: Simple and used for small quantities and complex jobs.**
- **Permanent mold casting: Molten metal is poured into permanent metal mold.**
  - **Finer grain structure and strength due to fast cooling.**
  - **Less shrinkage and porosity.**
  - **More shrinkage and simple parts only.**
- **Die casting: Molten metal forced into molds under pressure.**
  - **Almost finished parts, automatic.**
  - **Good tolerance and surface finish.**
  - **Fine grain structure.**

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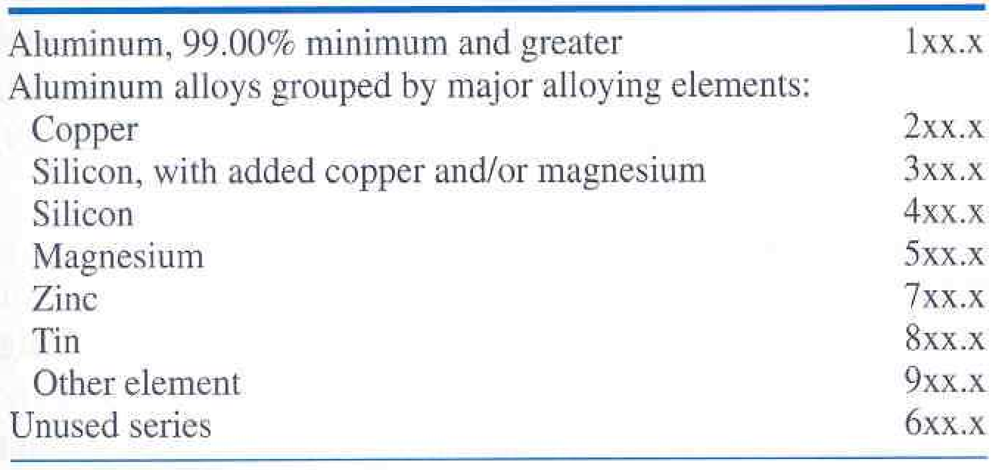
Aluminum Casting Alloy Composites

- **Composition of casting alloys differs greatly from wrought alloys**
- **Casting properties and mechanical properties are of primary interest.**
- **Denoted as 4 digits with a period between last two digits.**

Table 9.9



Aluminum, 99.00% minimum and greater	1xx.x
Aluminum alloys grouped by major alloying elements:	
Copper	2xx.x
Silicon, with added copper and/or magnesium	3xx.x
Silicon	4xx.x
Magnesium	5xx.x
Zinc	7xx.x
Tin	8xx.x
Other element	9xx.x
Unused series	6xx.x

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Copper Alloys

- **General properties of Copper: Good electrical and thermal conduction, ease of fabrication, corrosion resistance, medium strength.**
- **Production of copper:**
  - ➢ **Copper sulfide concentrates are smelted.**
  - ➢ **Copper sulfide is converted to blister copper by blowing air through matte.**
  - ➢ **Impurities in blister copper removed as slag in refining furnace ➡ tough pitch copper.**
  - ➢ **Tough pitch copper is further refined electrolytically.**

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Classification of Copper Alloys

- **Numbers C10100 to C79900 designate wrought alloys.**
- **Numbers C80000 to C99900 designate casting alloys.**

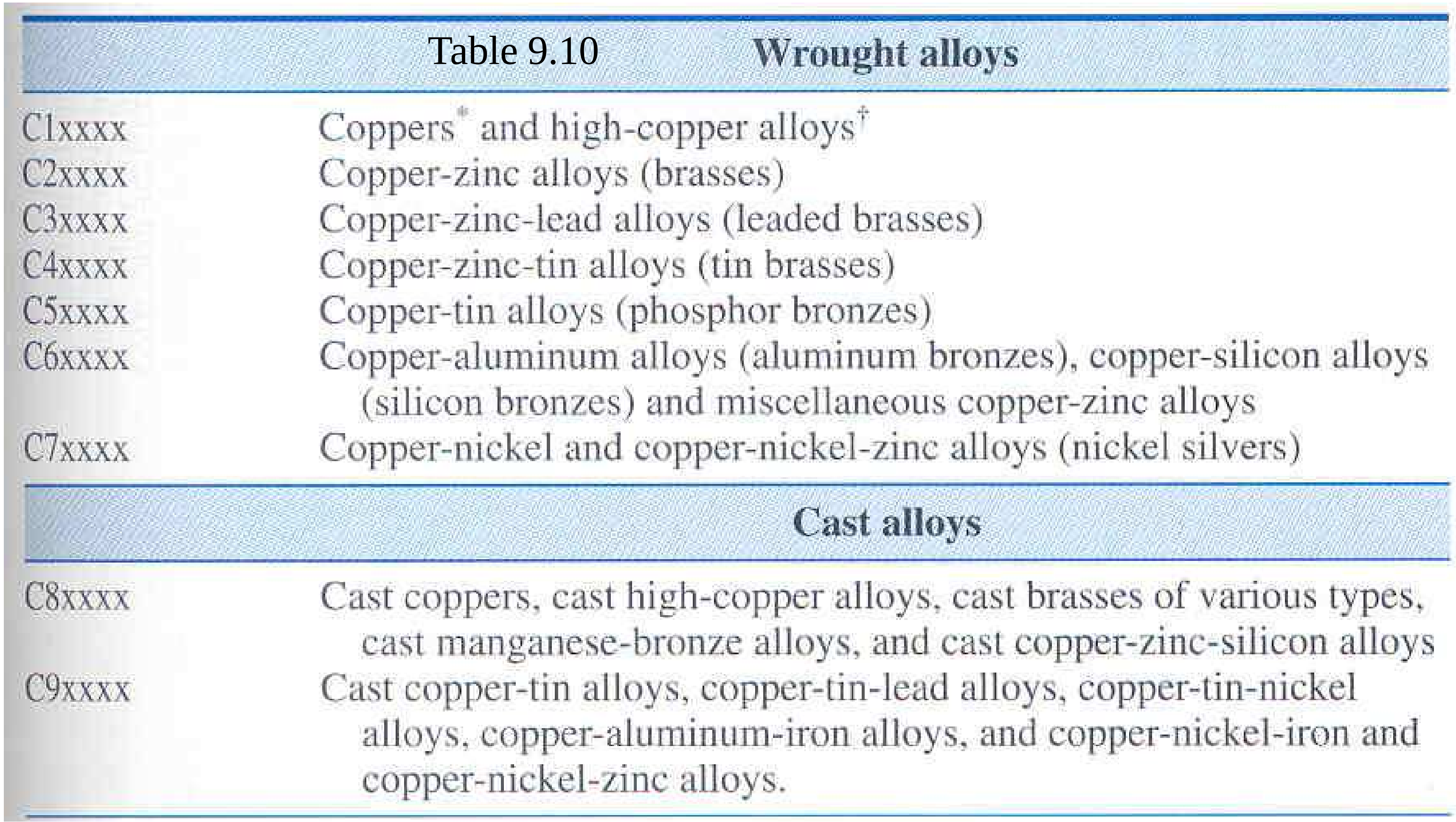

Table 9.10

	Wrought alloys
C1xxxx	Coppers* and high-copper alloys†
C2xxxx	Copper-zinc alloys (brasses)
C3xxxx	Copper-zinc-lead alloys (leaded brasses)
C4xxxx	Copper-zinc-tin alloys (tin brasses)
C5xxxx	Copper-tin alloys (phosphor bronzes)
C6xxxx	Copper-aluminum alloys (aluminum bronzes), copper-silicon alloys (silicon bronzes) and miscellaneous copper-zinc alloys
C7xxxx	Copper-nickel and copper-nickel-zinc alloys (nickel silvers)
	Cast alloys
C8xxxx	Cast coppers, cast high-copper alloys, cast brasses of various types, cast manganese-bronze alloys, and cast copper-zinc-silicon alloys
C9xxxx	Cast copper-tin alloys, copper-tin-lead alloys, copper-tin-nickel alloys, copper-aluminum-iron alloys, and copper-nickel-iron and copper-nickel-zinc alloys.

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Unalloyed Copper

- **Electrolytic tough pitch copper is least expensive and used in production of wire, rod, and strip.**
- **Has 0.04% oxygen.**
- $Cu_2O + H_2 \xrightarrow[400^0C]{Heated} 2Cu + H_2O$
- **H_2O causes inner holes and blisters.**
- **Copper cast in controlled reducing atmosphere**

Oxygen free high conductive Copper

(Alloy C10200)

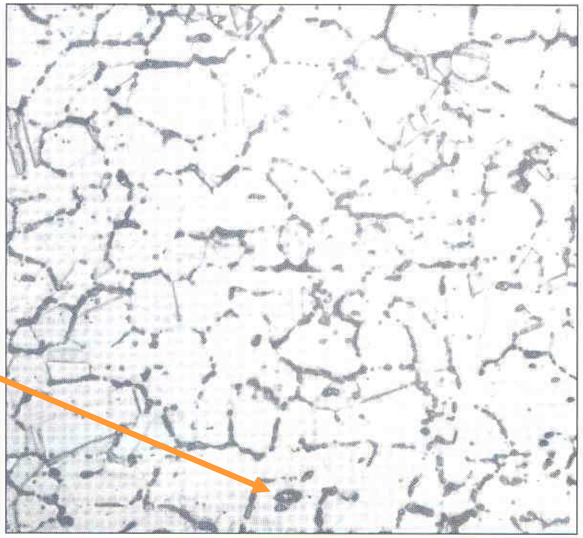

Figure 9.51

Courtesy of Amax Base Metals Research, Inc.

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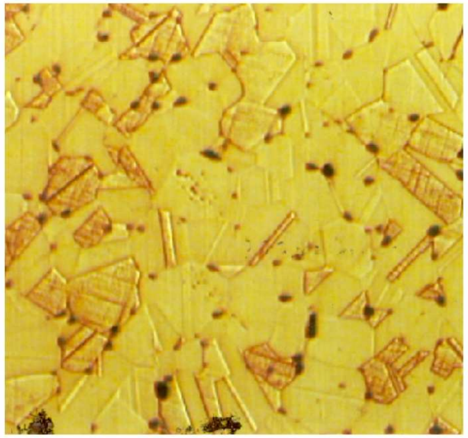
Copper Zinc Alloys

- **Copper forms substitutional solid solution with Zn till 35% Zn.**
- **Cartridge brass → 70% Cu & 30% Zn → single phase**
- **Muntz brass → 60% Cu & 40% Zn → two phase.**



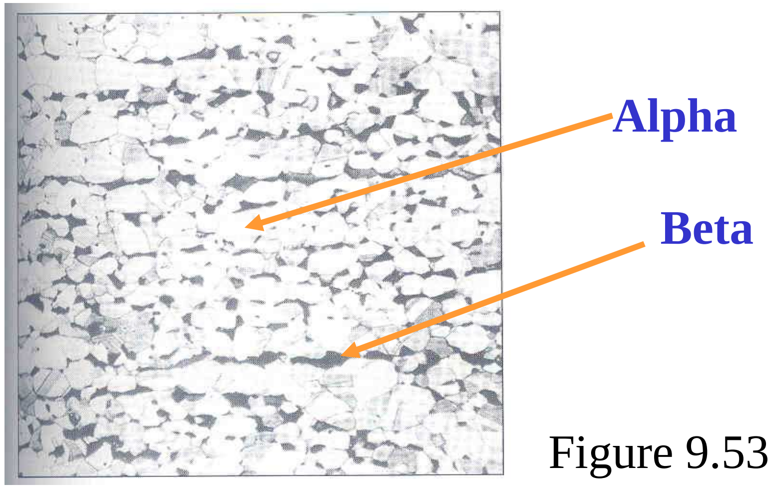


Figure 9.53

- **Zinc (0.5 to 3%) is always added to copper to increase machinability.**

Courtesy of Anaconda American Brass Co

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Other Copper Alloys

- **Copper-Tin Bronzes: 1 to 10% tin with Cu to form solid solution strengthened alloys.**
  - **Stronger and less corrosive than Cu-Zn bronzes.**
  - **Up to 16% Sn is added to alloys that are used for high strength bearings.**
- **Copper beryllium alloys: 0.6 to 2% Be and 0.2 – 2.5 % Cobalt with copper.**
  - **Can be heat treated and cold worked to produce very strong (1463 MPa) bronzes.**
  - **Excellent corrosion resistance and fatigue properties.**
  - **Used in springs, diaphragms, valves etc.**

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Stainless Steel

- **Excellent corrosion resistance in stainless steel is due to high (at least 12%) Chromium forming chromium oxide on surface.**
- **Ferrite stainless steel :**
  - ➢ **12-30% Cr**
  - ➢ **Structure is mainly ferritic (BCC α).**
  - ➢ **Cr extends α region and suppresses γ region forming γ loop.**

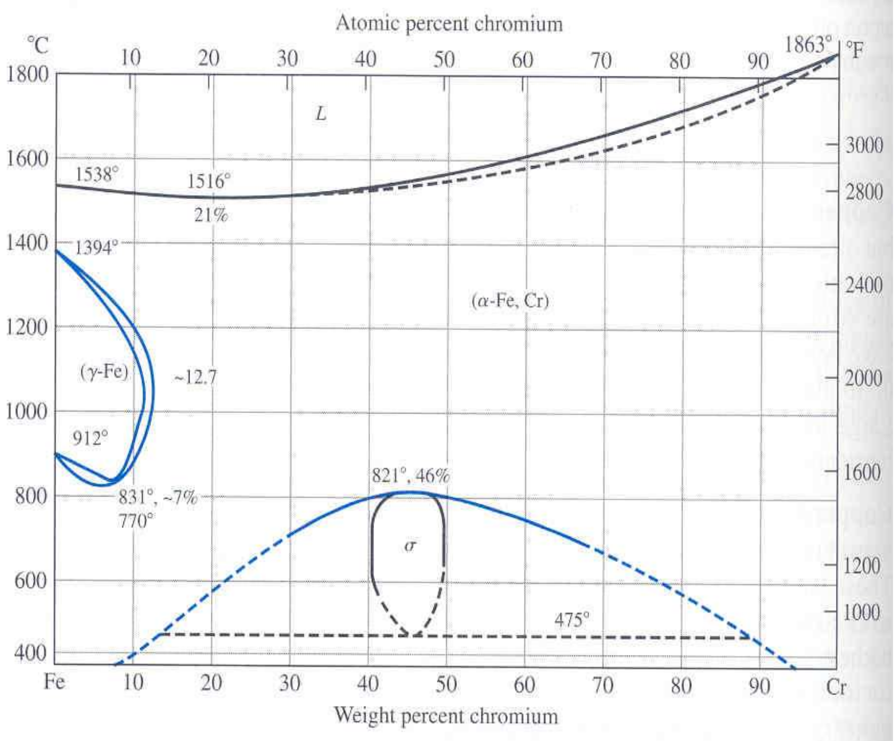

Figure 9.55

  - ➢ **Low cost high strength (517 MPa) and hence used in construction materials.**

After "Metals Handbook," vol. 8, 8th ed., American Society for Metals, 1973, p.291.

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Martensitic Stainless Steel

- **12 – 17% Cr and 0.15 – 1% C.**
- **Martensite formed from quenching from austenite region.**
- **Poor corrosion resistance.**
- **Heat treatment: Same as plain carbon steel.**
- **Tensile strength : 517 MPa to 1966 MPa.**
- **Used for machine parts, pumps, bearings, and valve parts.**
- **When carbon content is greater than 1%, α loop is enlarged.**

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Austenitic Region

- **Iron-Chromium (16-25%) – Nickel (7-20%) ternary alloy.**
- **Austenitic structure (FCC γ) remains austenitic at all temperature due to nickel.**
- **Better corrosion resistance than other steels.**
- **Tensile strength ⟶ 559-759 MPa.**
- **Used for chemical equipment, pressure vessels etc.**
- **Alloying element, columbium, prevents intergranular corrosion if the alloy is to be used for welding.**

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Cast Iron

- **General Properties: Contains 2-4% Carbon and 1-3% Si.**
- **Easily melted, very fluid, low shrinkage, easily machinable.**
- **Low impact resistance and ductility.**
- **Types of Cast Iron:**
    - ❖ **White cast iron**
    - ❖ **Gray cast iron**
    - ❖ **Malleable cast iron**
    - ❖ **Ductile cast iron**

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White Cast iron

- **Much of Carbon forms Iron Carbide instead of graphite up on solidification.**
- **Fractured surface appears white and crystalline.**
- **Low carbon (2.5 – 3%) and silicon (0.5 – 1.5%) content.**
- **Excellent wear resistance.**

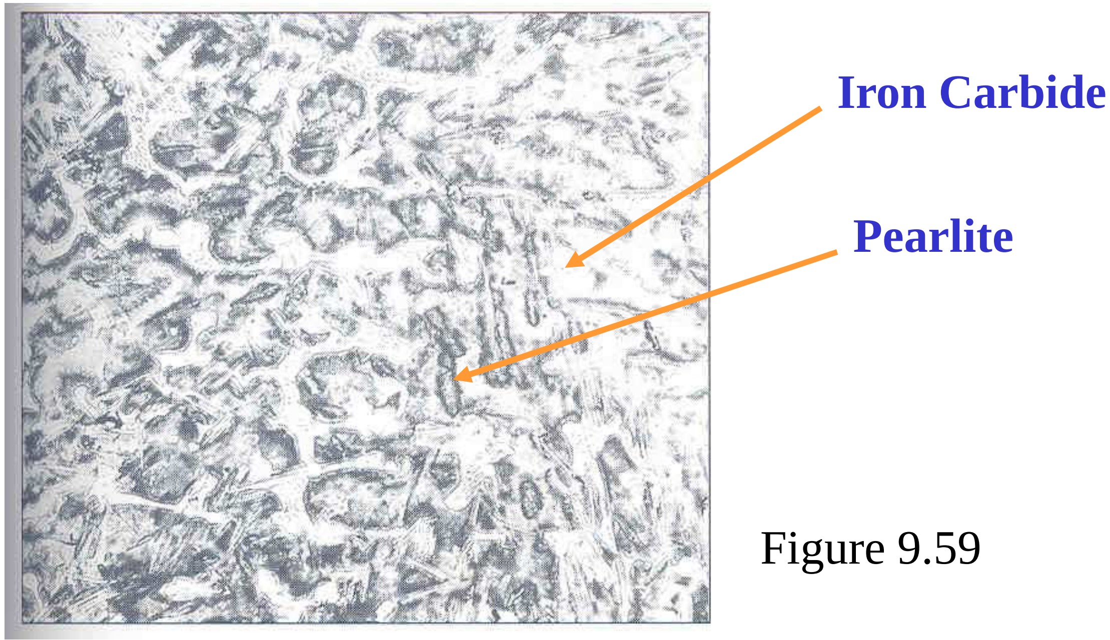

Figure 9.59

Courtesy of central Foundry

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Gray Cast Iron

- **Carbon exceeds the amount that can dissolve in austenite and precipitate as graphite flakes.**
- **Fractured surface appears gray.**
- **Excellent machinability, hardness and wear resistance, and vibration damping capacity.**
- **2.5 – 4% C and 1 – 3% Si (Promotes formation of graphite).**

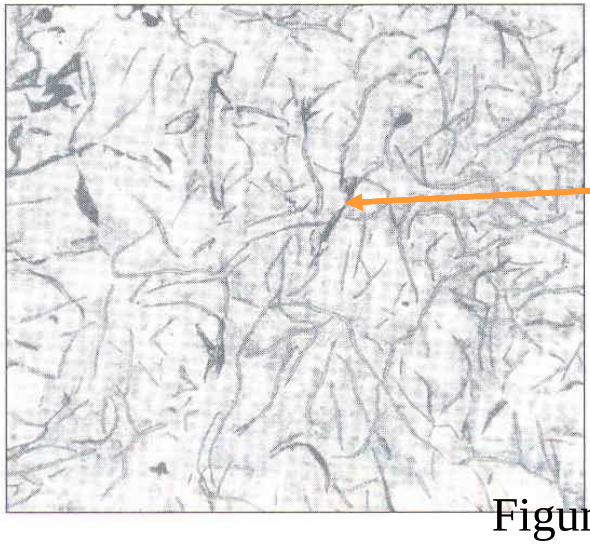

Figure 9.60

Graphite Flakes

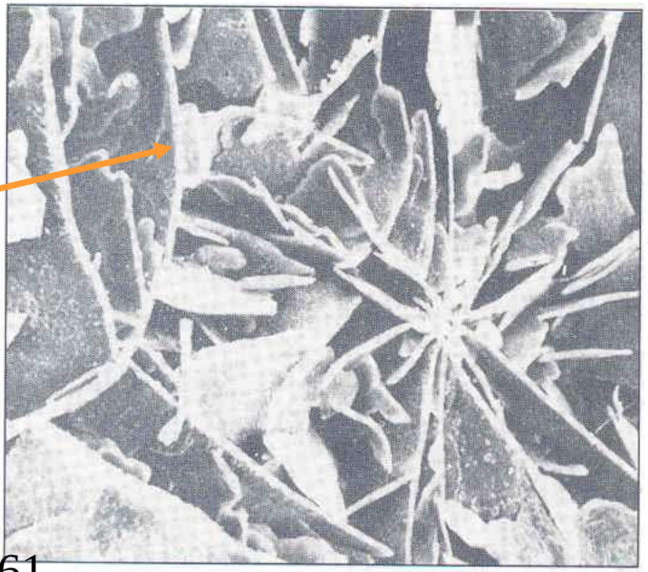

Figure 9.61

After "Metals Handbook," vol. 7, 8th ed., American Society for Metals, 1972, p.82.

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Ductile Cast iron

- Has processing advantages of cast iron and engineering advantages of steel.
- Good fluidity, castability, machinability, and wear resistance.
- High strength, toughness, ductility and hardenability (due to spherical nodules of graphite).
- 3-4% C and 1.8 – 2.8 % Si and low impurities.
- Bull’s eye type microstructure.

Figure 9.63

After “Metals Handbook,” vol. 7, 8th ed., American Society for Metals, 1972, p.88.

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Malleable Cast Iron

- **2-2.6 % C and 1.1 – 1.6% Si.**
- **White cast iron is heated in malleablizing furnace to dislocate carbide into graphite.**
- **Irregular nodules of graphite are formed.**
- **Good castability, machinability, moderate strength, toughness and uniformity.**

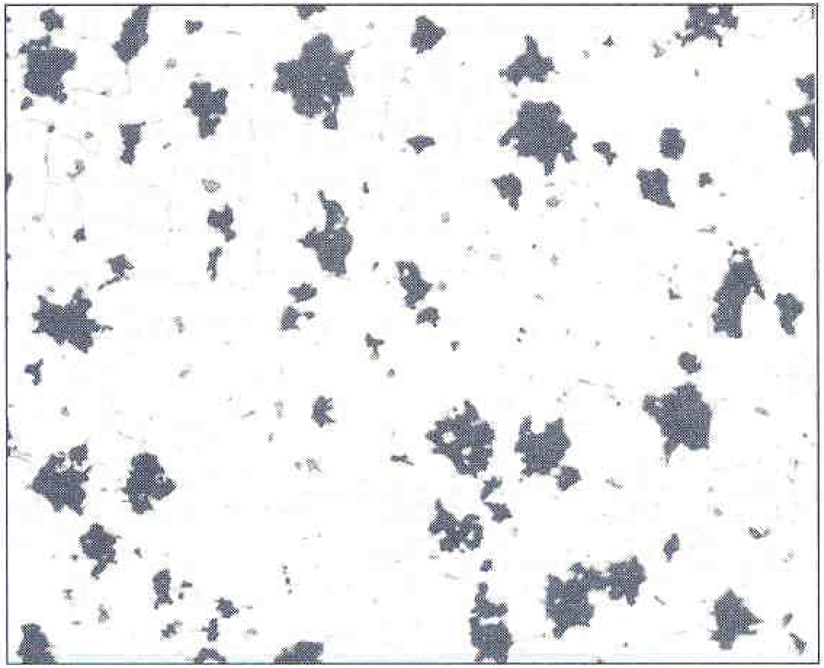

Figure 9.65

After "Metals Handbook," vol. 7, 8th ed., American Society for Metals, 1972, p.95.

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Heat Treatment

- **Heat treatment of white irons to produce malleable irons are**
  - **Graphitization: Castings heated above the eutectoid temperature (940^{0}C) and held for 3 to 20h depending on the composition and structure.**

    white iron $\longrightarrow$ graphite and austenite.
  - **Cooling :**
    - **Ferritic malleable iron: Fast cooled from 740-760^{0}C and then slowly cooled.**
    - **Pearlitic malleable iron: Slowly cooled up to 870^{0}C and then air cooled.**
    - **Tempered martensitic malleable iron: Casting cooled in furnace to a quenching temperature and homogenized and then quenched in agitated oil.**

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Magnesium, Titanium and Nickel Alloys

- **Magnesium Alloys:**
  - **Low density metal, high cost, low castability, low strength, poor creep, fatigue and wear resistance.**
  - **Two types: wrought alloys (sheet, plate, extrusion) and casting alloys (casting).**
  - **Designated by two capital letters and two or three numbers.**
  - **First two letters indicate two major alloying elements.**
  - **The numbers indicate wt% of alloying elements.**

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Structure and Properties of Magnesium Alloys

- **Limited cold working due to HCP structure.**
- **Usually hot worked.**
- **Al and Zn are added to increase strength.**
- **Alloying with rare earth elements (cerium) produces rigid boundary network.**
- **Tensile strength 179 – 310 MPa.**
- **Elongation – 2 to 11%**

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Titanium Alloys

- **Low density and high strength**
- **Expensive – used for aircraft applications.**
- **Superior corrosion resistance.**
- **Special technique needed to work with metal.**
- **HCP at room temperature. Transforms to BCC at 883^{0}C.**
- **Al and O increase transformation temperature.**
- **Tensile strength – 662 to 862 MPa**

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Nickel Alloys

- **Expensive, good corrosion resistance and high formability.**
- **Commercial Nickel and Monel alloys: good weldability, electrical conductivity and corrosion resistance.**
- **Nickel + 32% Cu ⟶ Monel alloy (strengthens nickel).**
- **Nickel based super alloys: High temperature creep resistance and oxidizing resistance for gas turbine parts.**
- **50 -60 % Ni + 15-20% Cr + 15-20% Co + 1-4% Al + 2-4% Ti.**
- **3 phases – Gamma austenite, gamma prime, carbide particles.**

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Intermetallics

- **Unique combination of properties**
- **Examples: Nickel aluminide**
  Iron aluminide
  Titanium aluminide

High temperature applications

- **Low density, good high temperature strength, less corrosion but brittle.**
- **0.1 % Boron and 6-9 % Cr added to reduce embrittlement and to increase ductility.**
- **Applications : Jet engine, pistons, furnace parts, magnetic applications (Fe_3Si) and electronic applications ($MoSi_2$)**

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Shape Memory Alloys (SMA)

- **SMA recover predefined shape when subjected to appropriate heat treatment.**
- **Recovers strain and exerts forces**
- **Examples: AuCd, Cu-Zn-Al, Cu-Al-Ni, Ni-Ti**
- **Processed using hot and cold forming techniques and heat treated at 500-800 ^{0}C at desired shape.**
- **At high temperature ---Regular cubic microstructure (Austenite)**
- **After cooling – Highly twinned platelets (Martensite)**

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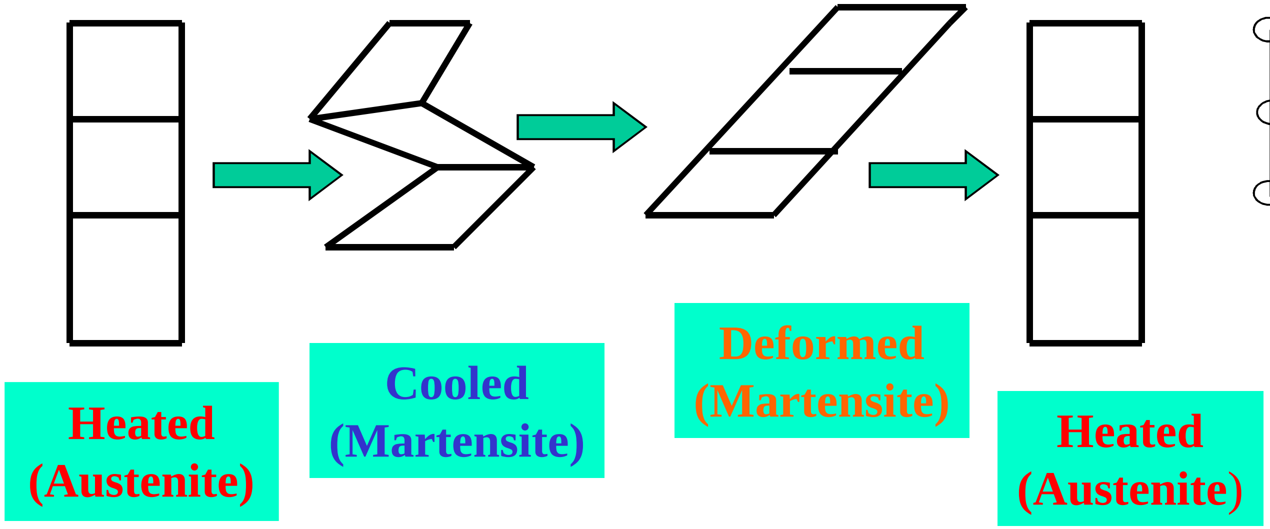
Shape Memory Effect

- **SMA easily deformed in martensite state due to twin boundaries and deformation is not recovered after load is removed.**
- **Heating causes Martensite ⟷ Austenite transformation so shape is recovered.**
- **Effect takes place over a range of temperature.**

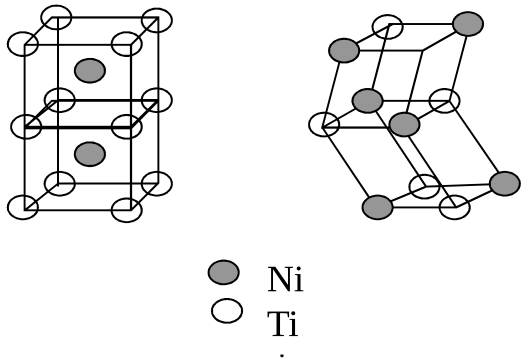


Heated (Austenite)

Cooled (Martensite)

Deformed (Martensite)

Heated (Austenite)



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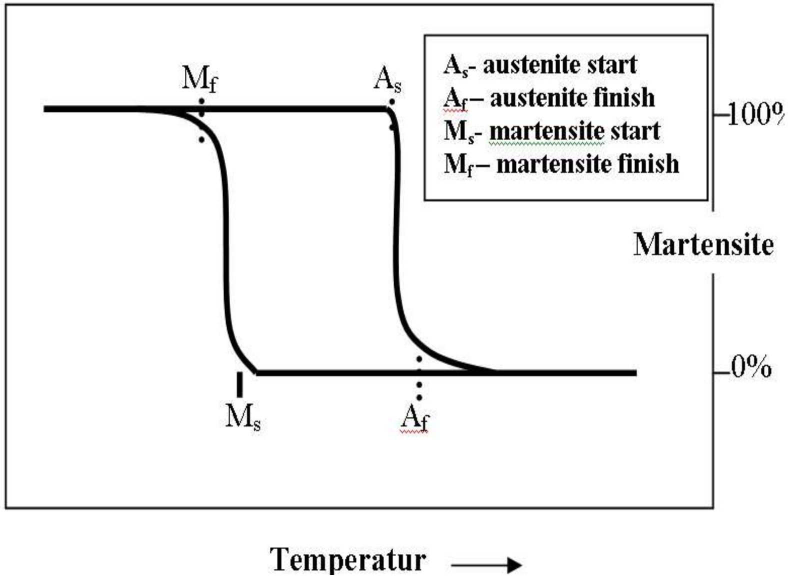
SMA - Hysterisis

- **Heating and cooling temperatures do not overlap – Exhibits hysterisis**
- **Applied stress may deform and transform SMA to martensite – stress induced transformation**
- **Shape is recovered when stress is released**
- **Nitonol (NiTi) is commonly used SMA**
  - **Shape memory strain of 8.5%**
  - **Non-magnetic, corrosion resistant**
- **Applications: Vascular stents Coffeepot thermostats, eyeglass frames orthodontics, vibration damper surgical tools**



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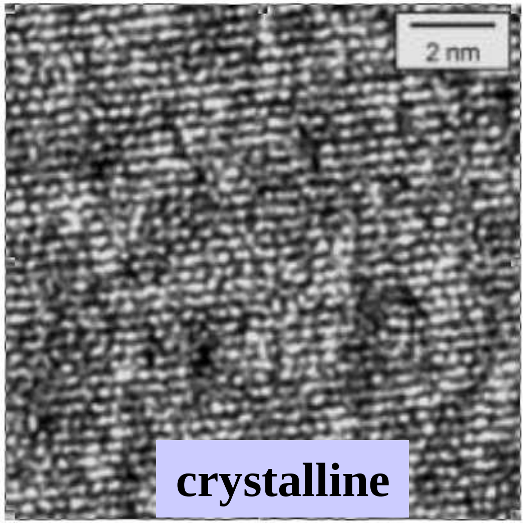
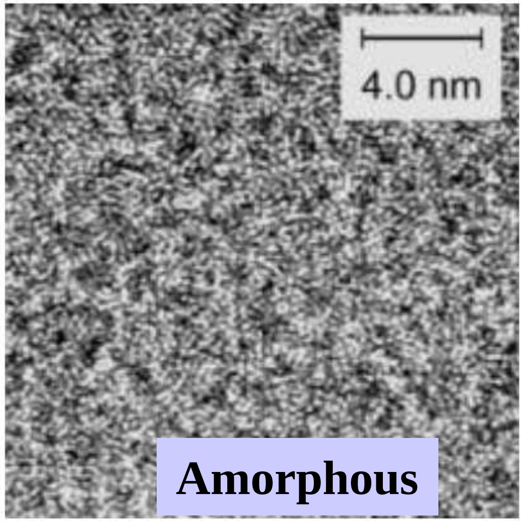
Amorphous Metals

- **Atoms arranged in random manner in metals under special circumstances**
- **Produced by rapid quenching (10 ^{5} K/s) – No time to form crystals.**
- **Till now only small pieces could be produced**
- **No dislocation activity : Very hard, perfectly plastic, high dimensional accuracy (no shrinkage)**
- **Applications:**
  - **surgical knives**
  - **Golf clubs**



crystalline



Amorphous

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Biomedical Applications: Biometals

- **Biometals come in direct contact with human body fluids.**
  - **Used to replace tissue**
  - **Support damaged tissue while heeling**
  - **Filler material**
- **Biocompatibility : Internal environment of human body is highly corrosive**
  - **Metals degrade and release harmful ions**
  - **Chemical stability, corrosion resistance, non-carcinogenity and non-toxicity is called biocompatibility.**
- **High fatigue strength is desired.**
- **Pt, Ti, Zr have good biocompatibility.**
- **Co, Cu, Ni are toxic**

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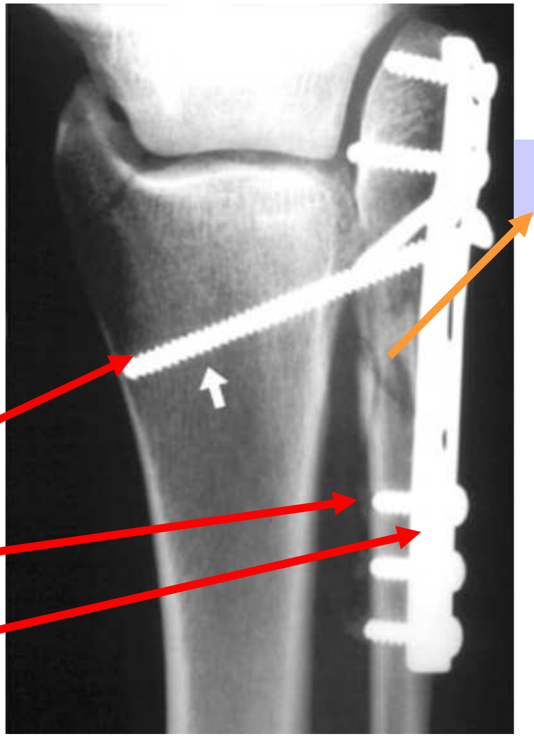
Stainless Steels as Biometals

- **316 L stainless steel (cold worked, grain size of minimum 5) is used most often**
  - ➢ **18Cr-14Ni-2.5Mo---F138**
- **Inexpensive, easily shaped**
- **limited corrosion resistance inside the body**
  - ➢ **removed after healing**
  - ➢ **Used as bone screws**



Bone plate

Spine plate

Intermedullary nail

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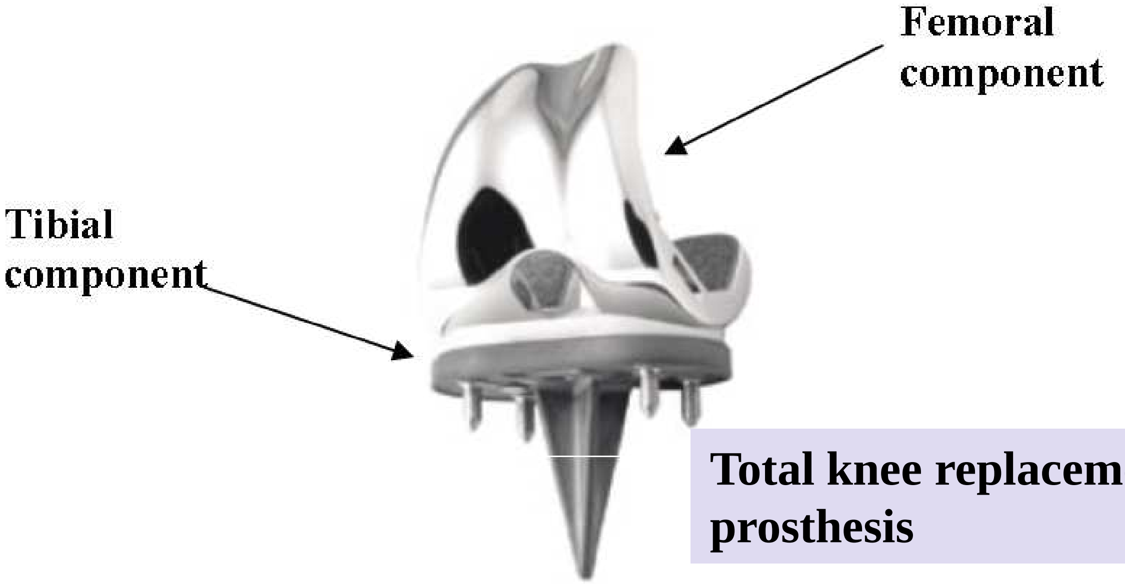
Cobalt Based Alloys

- Co-28Cr-6Mo
  Co-20Cr-15W-10Ni
  Co-28Cr-6Mo-heat treated
  Co-35Ni-20Cr-10Mo

Cr promotes long term
Corrosion resistance

Ni and W improve machinability
And fabrication

- Initially hot worked and then cold finished
- Used in permanent fixation devices



Total knee replacement
prosthesis

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Titanium Alloys

- **Easily formed, outstanding corrosion resistance**
- **Low elastic modulus, highly biocompatible**
- **Pure Ti is used in low strength applications**
- **Alpha-beta alloys of Ti like Ti-6Al-4V (F1472) are strengthened by solution heat treatment.**
- **Poor wear resistance and notch sensitivity**
- **Beta alloys have low elastic modulus**
- **Ion implantation improves wear resistance**

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Issues in Orthopaedic Applications

- **High yield strength, fatigue strength and hardness of implants is desired.**
  - **Implant should support healing bone**
- **Low elastic modulus is desired**
  - **Implant and bone should carry proportionate amount of load**
  - **Implant should not shield the bone from load**
  - **Stress shielding stops remodeling of bone and weakens it.**
  - **Elastic modulus of bone is only 17 GPa while most alloys have elastic modulus greater than 100 GPa.**
- **Wear causes metallic toxicity**
  - **Co-Cr alloys have good wear resistance**