Materials for Automobiles

Lec 5
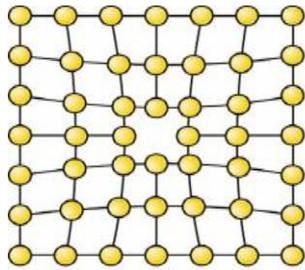
Date : 18 August 2011

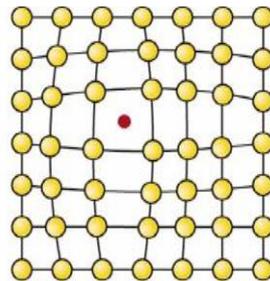# Plan

	Review of Earlier Concepts
	Defects in Crystal structure of metals
	Heat treatment of steel

Classification of Defects

	Point Defects	0-D
	Line Defects - dislocations	1-D
	Surface Defects- grain boundaries	2-D
	Bulk Defects	3-D

Relative Size Range of the Different Classes of Defects

Point Defects

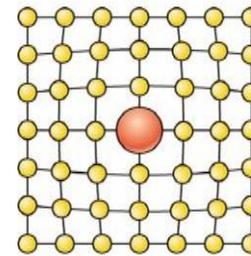|	
A	Vacancies
B	Interstitials
C	Substitutionals

(a)　　(b)　　(d)

VACANCIES ARE THERMALLY GENERATED

$$\frac{n_v}{N} = C\,e^{\left[-\frac{E_v}{kT}\right]}$$

where n_v = *number of vacancies per cubic meter of metal*

N = *total number of atom sites per cubic meter of metal*

E_v = *activation energy to form a vacancy, eV*

T = *absolute temperature, K*

k = *Boltzmann's constant* = $8.62 x 10^{-5}$ *eV/K*

C = *constant*

– **POINT DEFECTS -- SOLID SOLUTIONS**

- **Solid solutions are the intermingling of different types of atoms on the same lattice.**

  - **Substitutional Solid Solutions -- Solute atoms substitute for solvent atoms in a crystalline lattice.**

- **Interstitial Solid Solutions -- Solute atoms fit into spaces between solvent atoms in a crystalline lattice.**

  - **Interstitial Solid Solutions occur only when very small atoms like hydrogen, carbon, nitrogen, Boron, oxygen can be "stuffed" into interstices between much larger solvent atoms.**

# "Hume-Rothery Rules" for Substitutional Solubility

- – 1. Diameters of the atoms must not differ by more than 15%.

- – 2. Crystal Structures of the two atoms must be the same or have the same coordination number.

- – 3. The difference in electronegativity of the two elements must be small.

- – 4. The two elements should have the same valence.
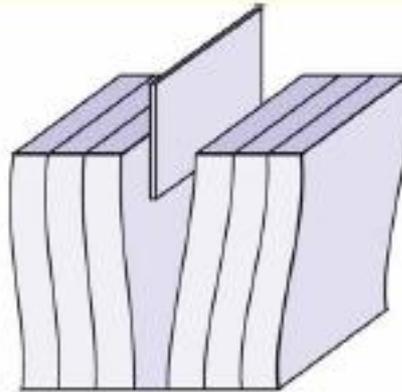
ONE DIMENSIONAL DEFECTS -- DISLOCATIONS

TWO MAIN TYPES OF DISLOCATIONS ARE THE EDGE DISLOCATION AND THE SCREW DISLOCATION.
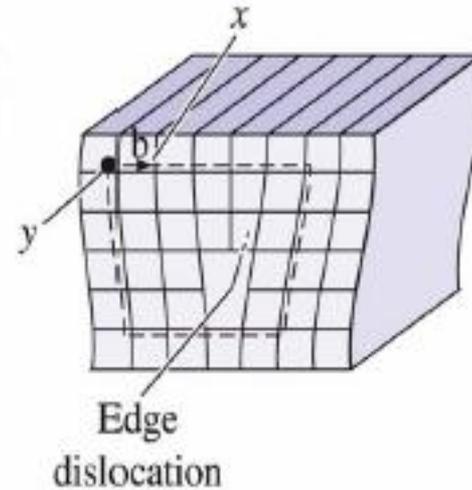
Edge Dislocation

a	Perfect crystal
b	Extra plane is partially inserted so that the bottom edge of extra plane forms the edge dislocation
c	A Burger's vector **b** is required to close the loop.
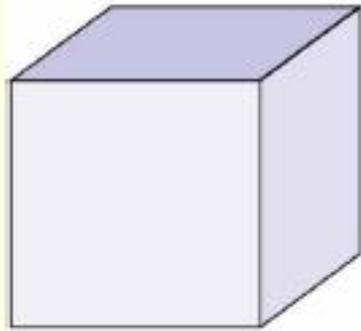
Edge dislocation

(a)   (b)   (c)
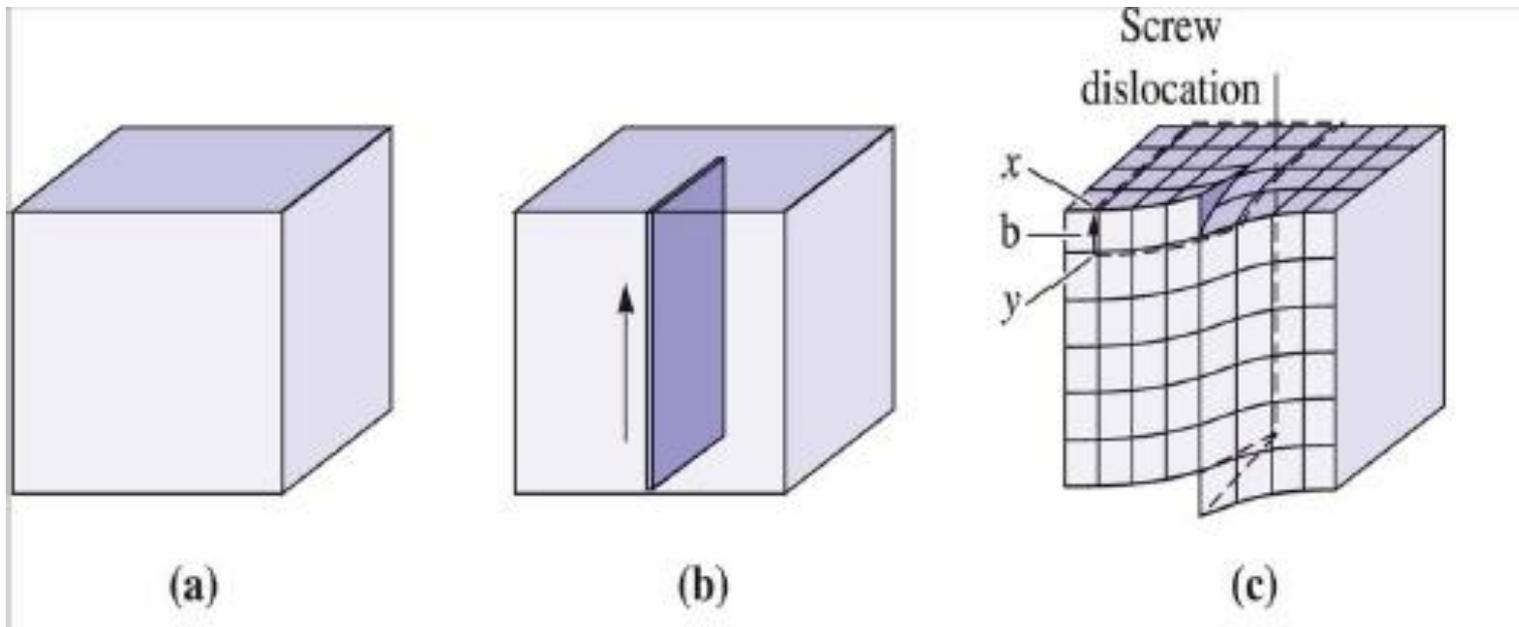
– Edge Dislocation

Atomic displacement or slip occurs in

the direction of the Burgers Vector !

The Burgers vector $\bar{b}$ is perpendicular

to the dislocation line.

$$\bar{b} \perp line$$

Screw Dislocation

a	Perfect crystal
b	Perfect crystal is cut and sheared one atom spacing , the line along which shearing occurs is the screw dislocation
c	A Burger's vector **b** is required to close the loop.

(a)   (b)   (c)

– **Screw Dislocation**

Atomic displacement or slip occurs in

the direction of the Burgers Vector !

*The Burgers vector $\bar{b}$ is parallel*

to the dislocation line.

$$\bar{b} \mid\mid line$$

FACTS ABOUT DISLOCATIONS:

- 1. A highly deformed metal will have miles of dislocation lines per cubic centimeter of metal.
- 2. Cold working creates dislocations and this strengthens metals because dislocation lines interfere with other dislocation motion.
- 3. Foreign atoms also block dislocation motion and solution strengthen crystals
- 4. Second phase precipitates block dislocations and further strengthen crystals.

Barriers to Dislocation Motion

FIG. 9-6   Illustration of the process of pushing a dislocation through an array of precipitates
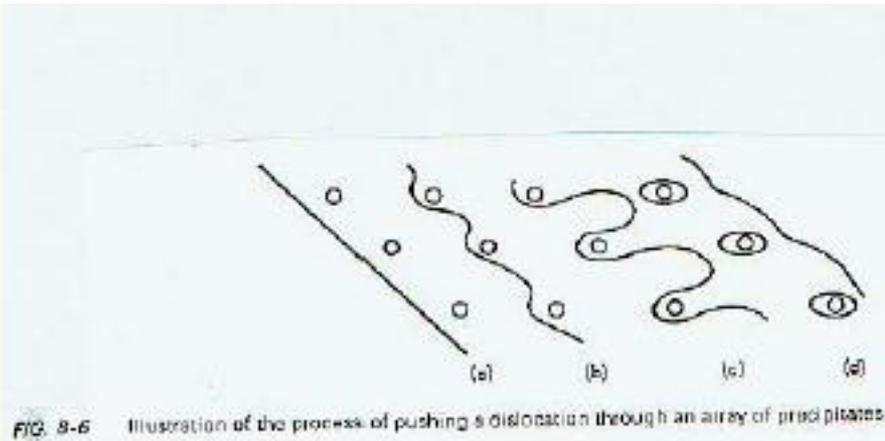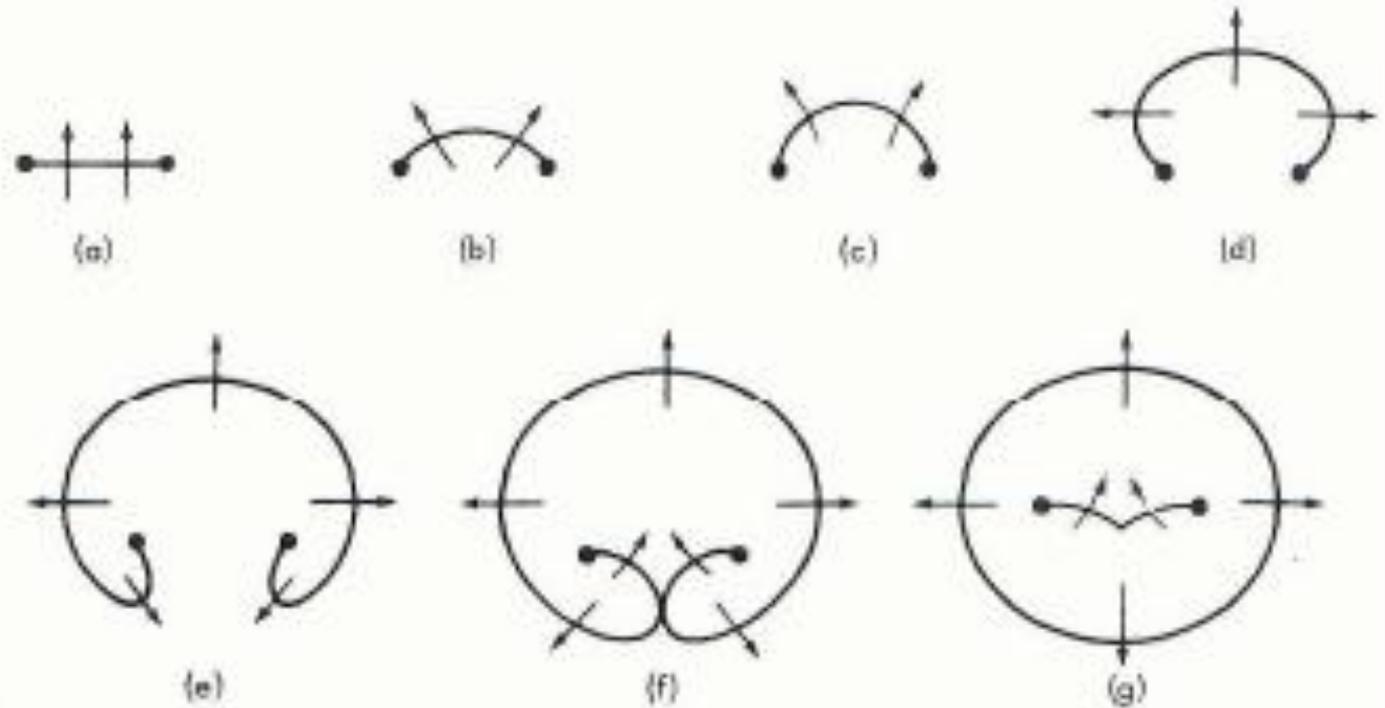
Dislocation Multiplication

FIG. 7-13 Sequence of dislocation positions during the operation of a Frank-Read source

TWO DIMENSIONAL DEFECTS - SURFACES

- ## SURFACES AND GRAIN BOUNDARIES
  - **Free Surfaces present significant energy only for ultra small particles at high temperatures.**
  - **Grain Boundaries separate grains of different orientation. GB's are created during solidification and contribute energy to the lattice. The smaller the grains, the larger the grain boundary surface area and the more unstable the material.**

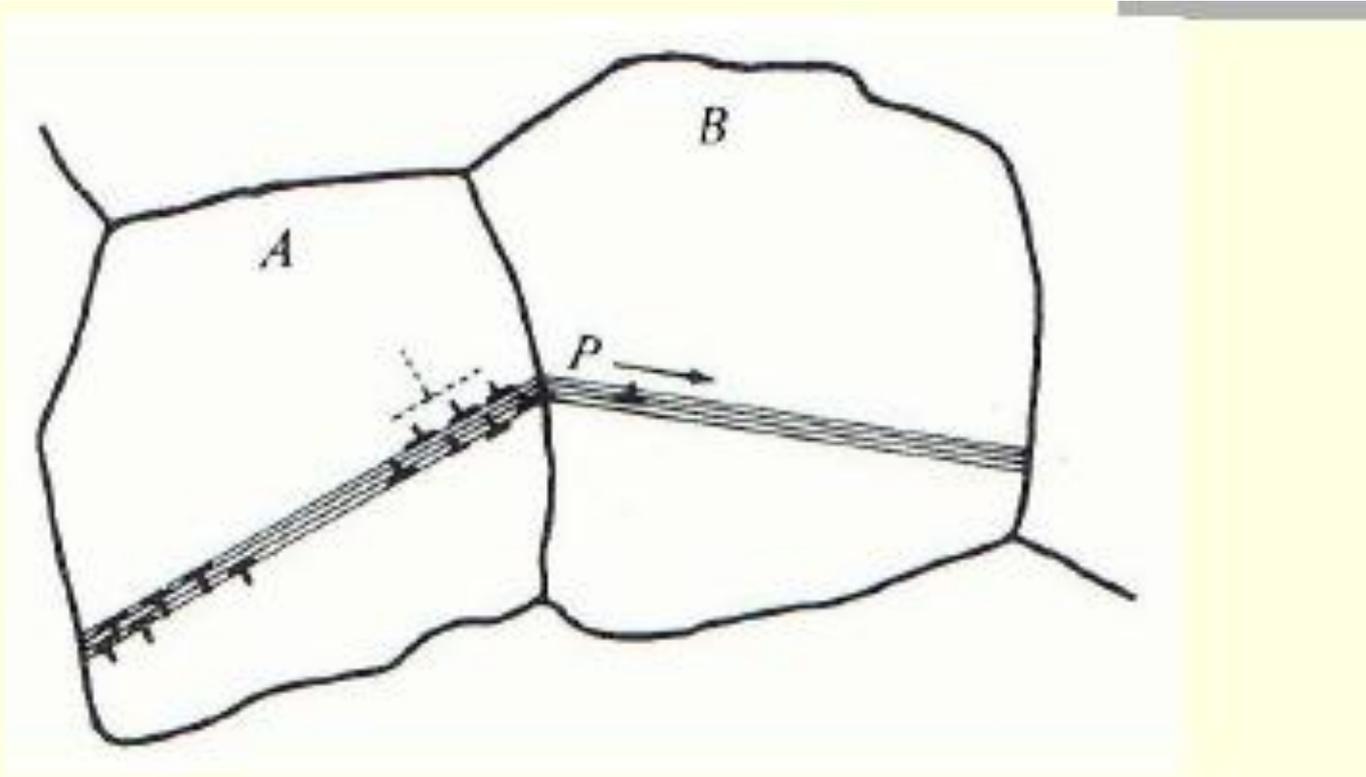# Effect of Grain Boundary and Grain size

FIG. 8-9 Schematic illustration of slip propagation from one grain to the next

– **Grain size determination (ASTM method)**

- **measure, N, the number of grains per square inch which are visible in a micrograph at a magnification of 100 X. Relate this number to a index by the following formula.**

$$N \; = \; 2^{(n-1)}$$

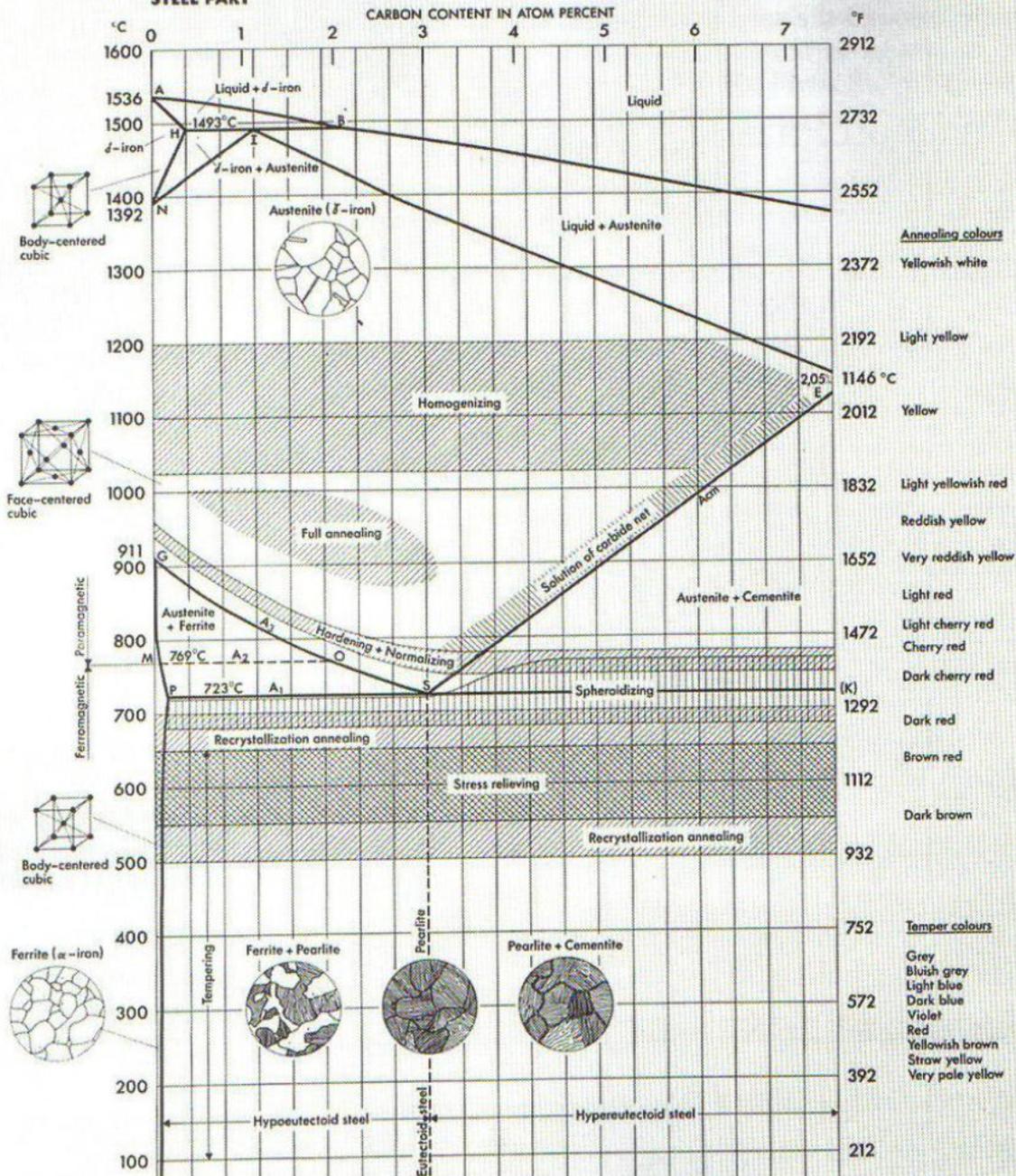*where N is the number of grains per square inch at 100 X.*

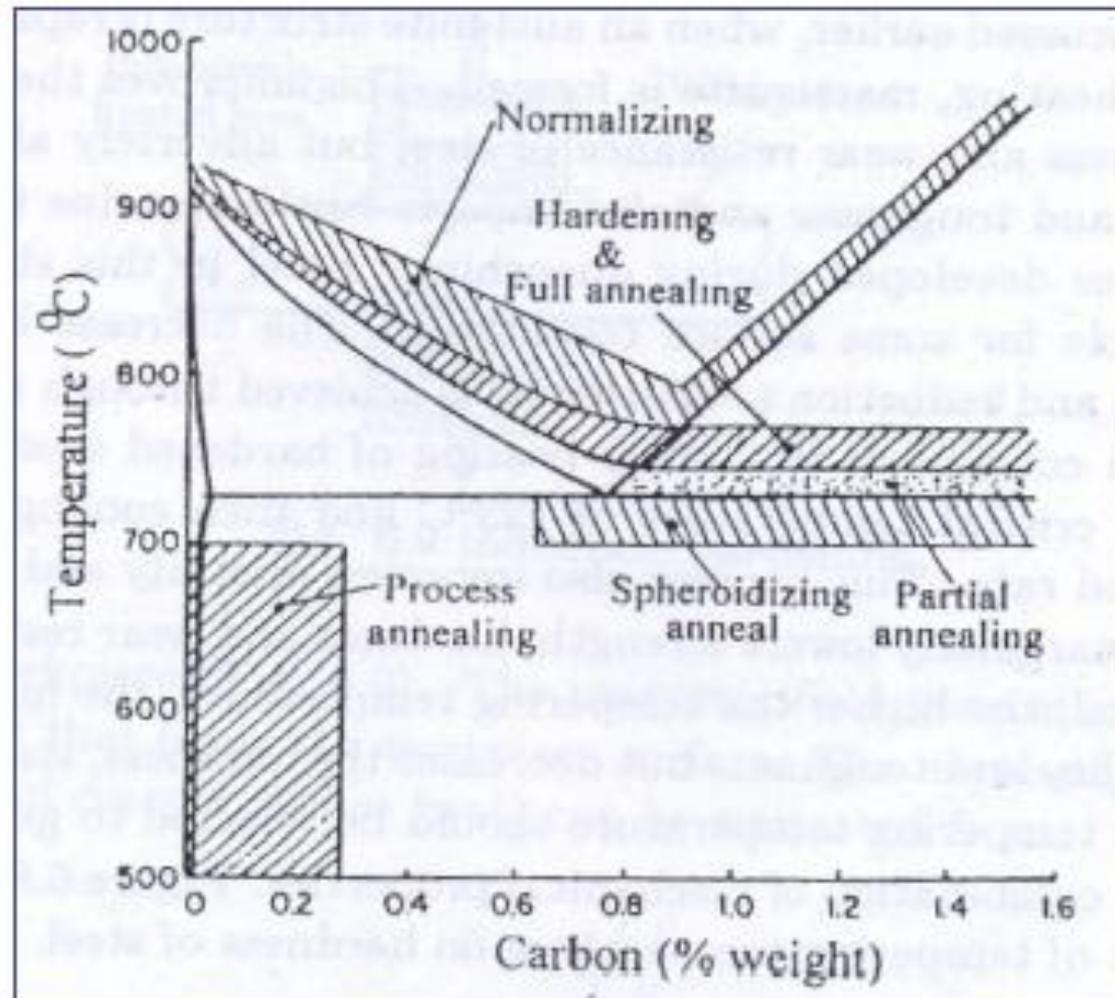*n is the ASTM Grain size number.*

Heat Treatment

	Metals and alloys may not posses all the desired properties in the finished product. Alloying and heat treatment are two methods which are extensively used for controlling material properties.
	In heat treatment, the microstructures of materials are modified. The resulting phase transformation influences mechanical properties like strength,ductility, toughness, hardness and wear resistance.
	Purpose of heat treatment is to increase service life of a product by increasing its strength of hardness, or prepare the material for improved manufacturability

IRON-CARBON EQUILIBRIUM DIAGRAM

STEEL PART

CARBON CONTENT IN ATOM PERCENT

°C		°F
1600		2912
1536	A — Liquid + δ–iron — B — Liquid	2732
1500	1493°C — H — I	
	δ–iron — δ–iron + Austenite	
1400	N — Austenite (γ–iron) — Liquid + Austenite	2552
1392		
Body-centered cubic		2372 — Yellowish white
1300		
1200	Homogenizing	2192 — Light yellow
	2,05 — 1146 °C	
1100	E	2012 — Yellow
Face-centered cubic		
1000	Full annealing — Solution of carbide net — Acm	1832 — Light yellowish red
		Reddish yellow
911	G	1652 — Very reddish yellow
900	Austenite + Ferrite — A₃ — Hardening + Normalizing	Light red
800	A₂ — Austenite + Cementite	1472 — Light cherry red
	M — 769°C — A₂ — O	Cherry red
	P — 723°C — A₁ — S — Spheroidizing — (K)	Dark cherry red
700		1292 — Dark red
	Recrystallization annealing	
		Brown red
600	Stress relieving	1112
		Dark brown
	Recrystallization annealing	
Body-centered cubic		932
500		
400	Ferrite + Pearlite — Pearlite — Pearlite + Cementite	752 — **Temper colours**
Ferrite (α–iron)	Tempering	Grey / Bluish grey / Light blue
300		572 — Dark blue / Violet / Red / Yellowish brown
200		Straw yellow / Very pale yellow
	Hypoeutectoid steel — Eutectoid steel — Hypereutectoid steel	392
100		212

**Ferromagnetic Paramagnetic**

Annealing colours

Heat treatments on phase diagram of steel

Annealing

◆ Annealing is performed to reduce hardness, remove residual stresses, improve toughness, restore ductility, and to alter various mechanical, electrical or magnetic properties of material trough refinement of grains.

◆ Cooling rate is very slow around 10°C per hour. Process is carried out in a controlled atmosphere of inert gas to avoid oxidation.

◆ Partial annealing is incomplete annealing and there is partial phase transformation however in sub-critical annealing there is no phase transformation.

◆ Used to achieve ductility in work hardened steels.
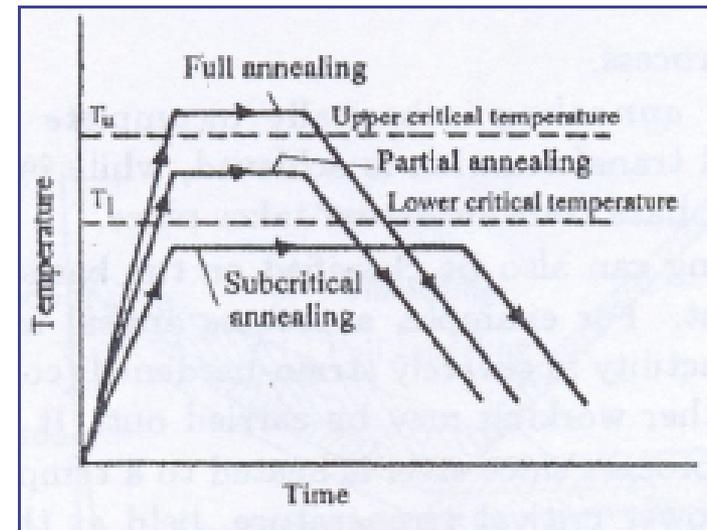
Normalizing

- The process is similar to annealing and is carried out to avoid excessive softness in the material.

- The material is heated above austenitic phase and then cooled in air . This gives relatively faster cooing and hence enhanced hardness and less ductility.

- In this process, austenite is decomposed in ferrite and carbide at relatively lower temperature and fine pearlite is produced.

- Normalizing is less expensive than annealing.

- In normalization variation in properties of different sections of a part is achieved.

- The selection of heat treatment operations is strongly influenced by the carbon content in th esteel.
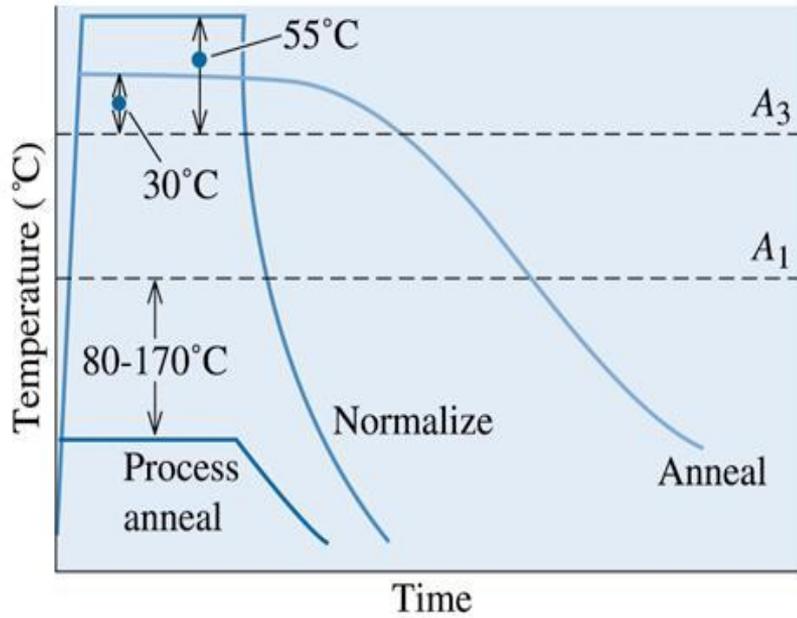
(a) **Hypoeutectoid**
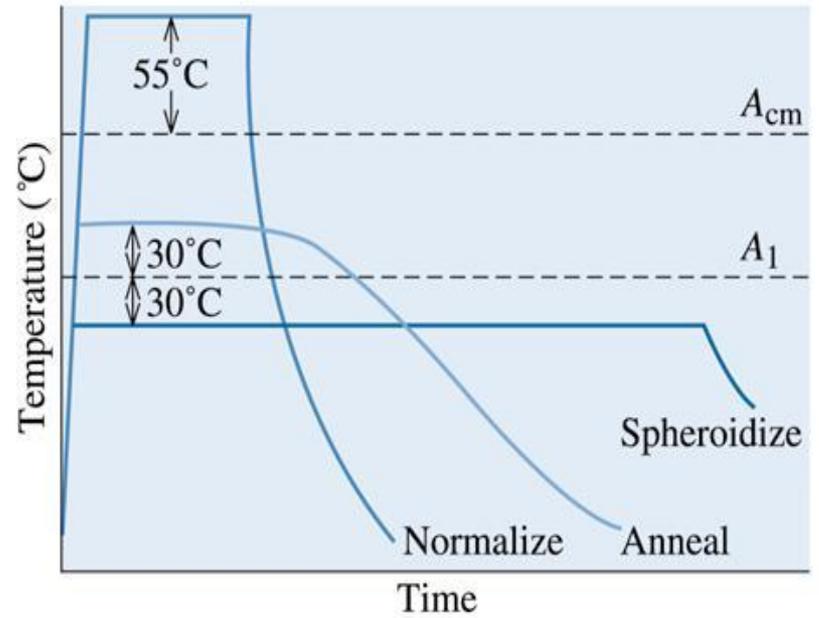
(b) **Hypereutectoid**

Normalizing and Full Annealing

	Normalizing 5 -10 ˚C/ min	Full annealed - ~1ºC/min
	To refine grain size To improve machinability	Fully soften material
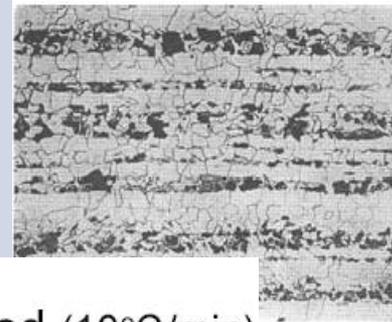
- Annealed (1ºC/min)
  - Yield pt: 250 MPa
  - % elongation/2 in: 37
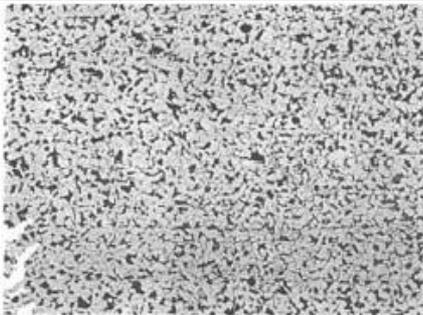
- Normalized (10ºC/min)
  - Yield pt: 310 MPa
  - % elongation/2 in: 35

# Spherodizing
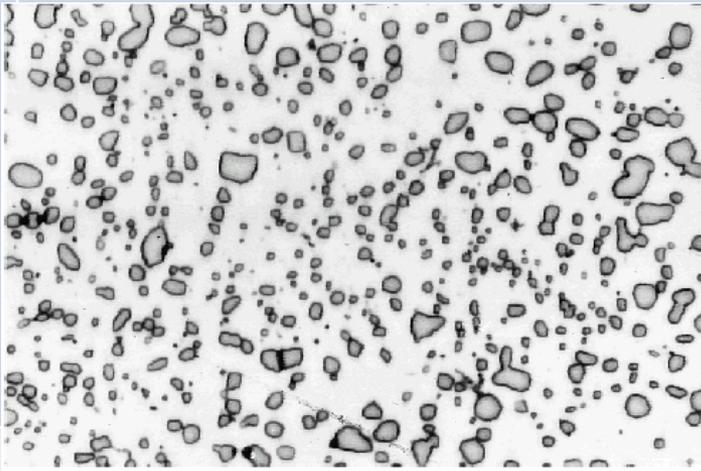
- **24 hrs @ temp just under A1**
  - -Carbides will spherodize if held for long time $<723^oC$
  - -Softens and puts steel in free machining condition

	Process Anneal	Stress relief
	• 1 hr @ 600-650°C • Recrystallizes cold worked ferrite • Yield Strength and UTS drastically reduced	• Up to 678°C with times up to 24 hrs; (use thermal blankets) • Done to relieve residual or internal stresses • Less chance of fatigue, stress corrosion, etc.
	• Sometimes used to selectively treat localized cold worked areas • Used in production of steel wire, nails etc	• Digestors and other pressure vessels have to be stress relieved to remove residual stresses associated with welds

Time-Temperature-Transformation (TTT) Diagram for Steel

Pearlite is produced if cooling rate is slow like in air or in a furnace. Fine pearlite is harder and less ductile than coarse pearlite.

Bainite is a very fine micro-structure, consisiting of ferrite and cementite, somewhat like Pearlite but have different morphology. This phase is stronger and more ductile than pearlite
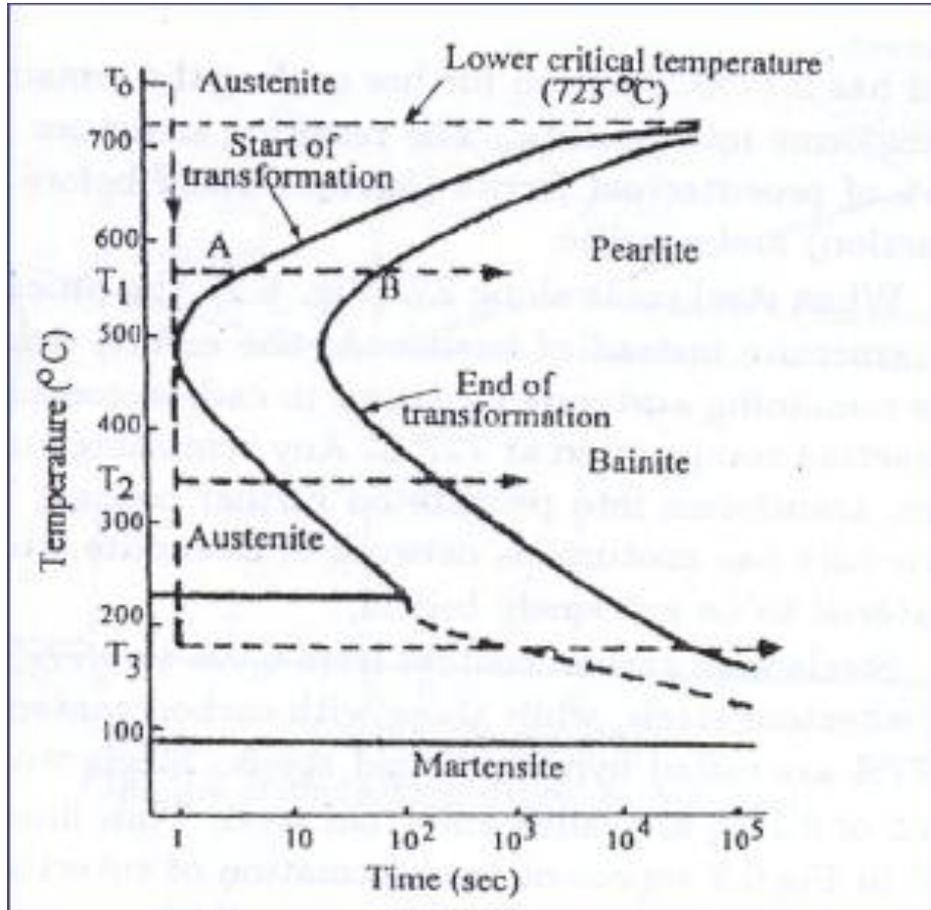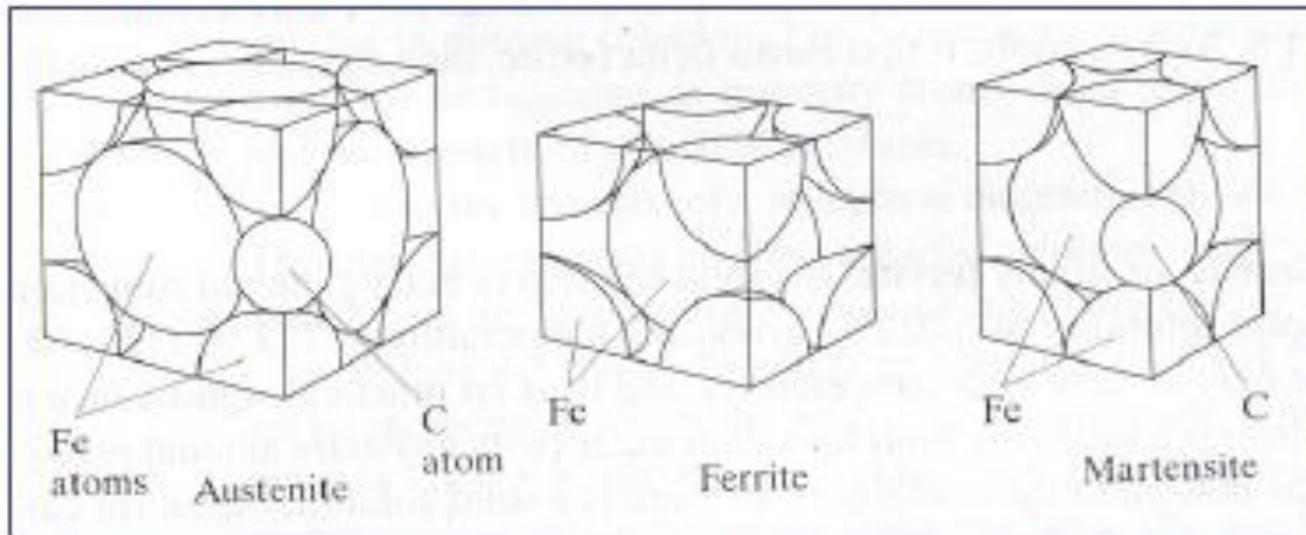
TTT diagram of Eutectic Steel

Modified TTT Diagram

- When austenite is
- cooled at a very high
- rate, such as quenching
- it in water, its FCC
- structure transforms to
- Body Centered
- Tetragonal (BCT) known
- as Martensite.
- I t is a extremely hard
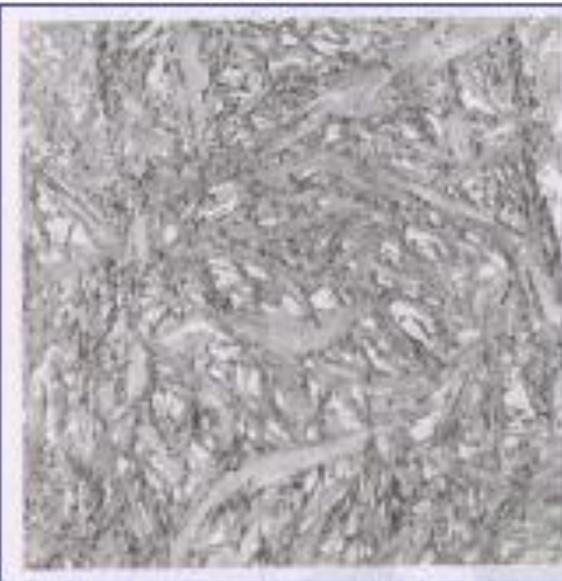- and brittle phase which
- lacks toughness, so
- limited use.

Microstructures

Fe atoms   Austenite   C atom

Fe   Ferrite
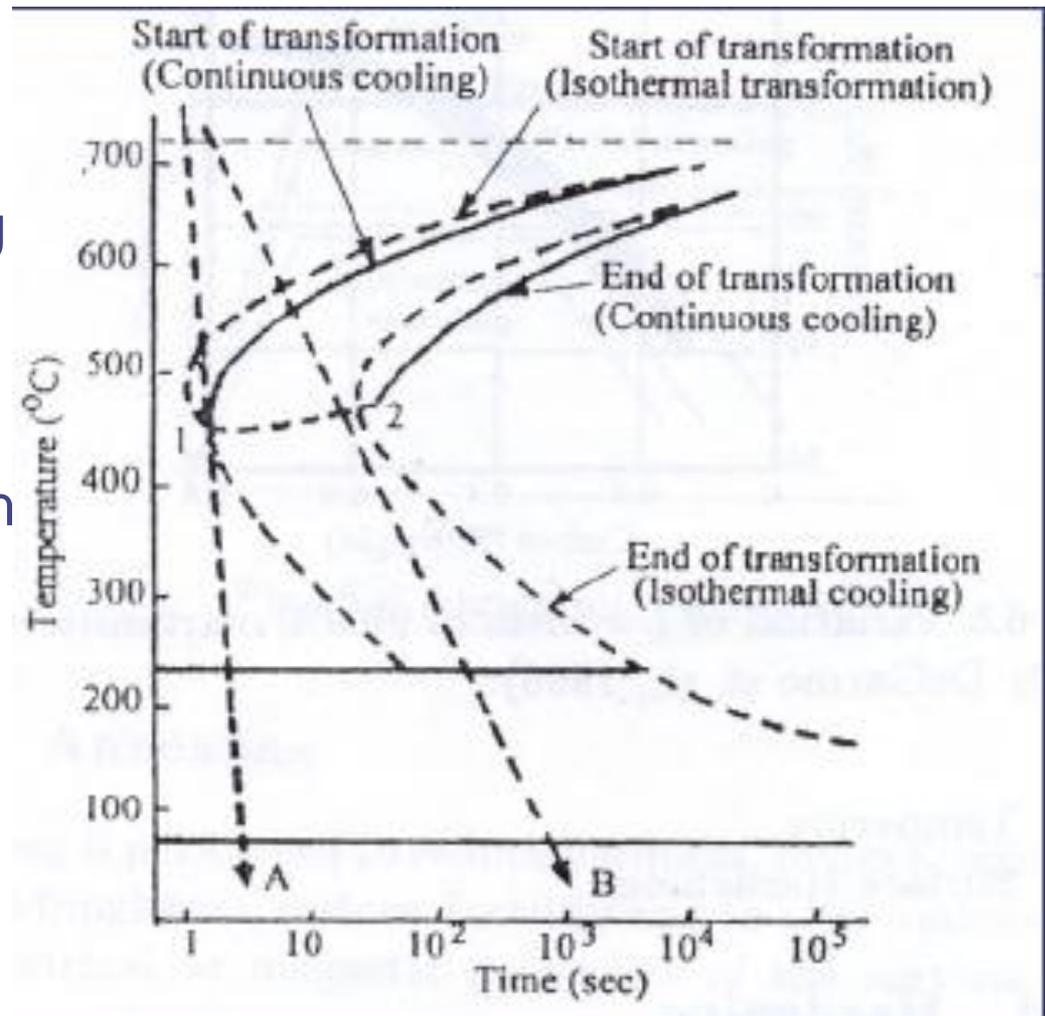
Fe   C   Martensite

Unit cells of FCC, BCC, BCT structures
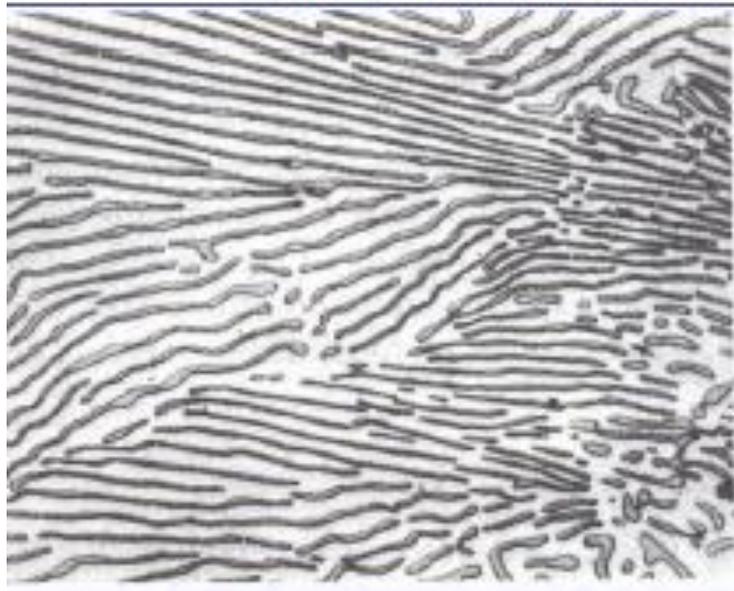
Pearlite

Martensite

Cooling Rates
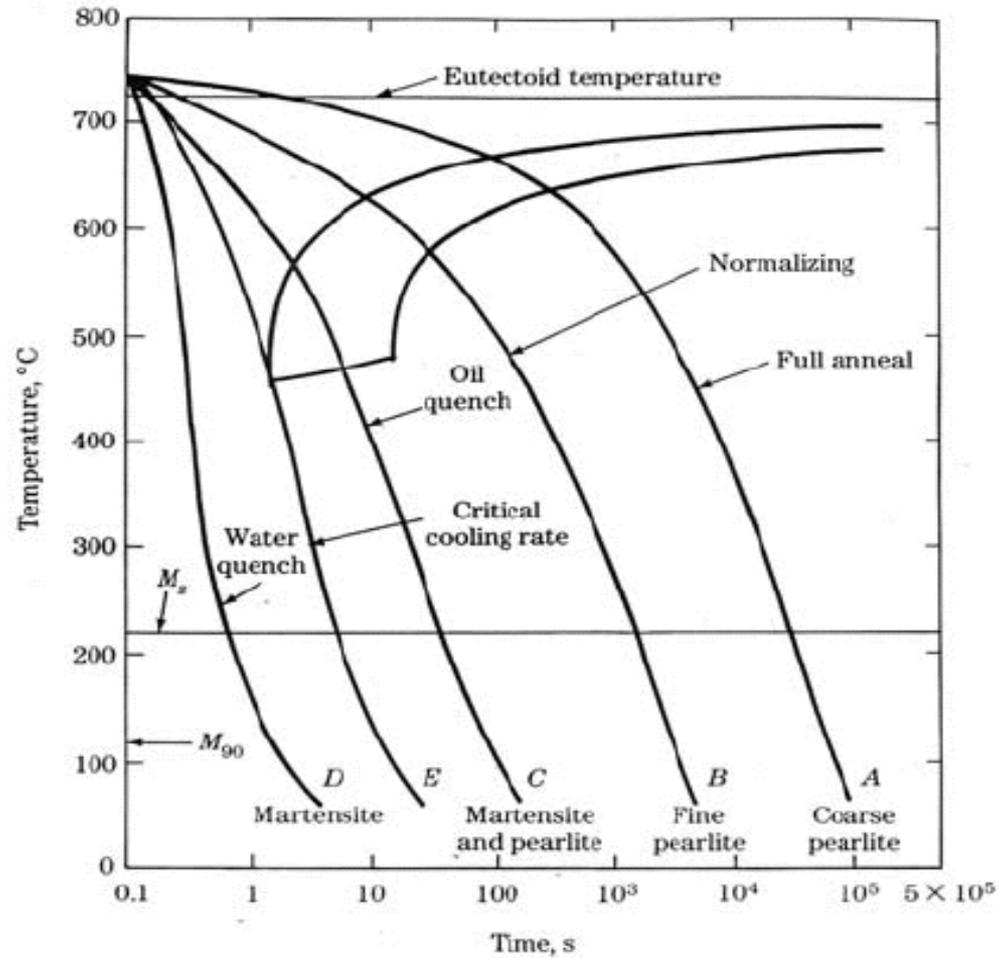
Coefficient of severity of quench: H			
Agitation	cooling medium		
	Oil	Water	Brine
None	0.25-0.30	0.9-1.0	2.0
Mild	0.30-0.35	1.0-1.1	2.0-2.2
Moderate	0.35-0.40	1.2-1.3	
Good	0.4-0.5	1.4-1.5	
Strong	0.5-0.8	1.6-2.0	
Violent	0.8-1.1	4.0	5.0

Grossman Number of Quenchants

Heat Transfer during Quenching. Heat removal from parts during quenching can be mathematically described in terms of the effective interface heat transfer coefficient. A quenchant must impart a sufficiently high interface heat transfer coefficient to produce a cooling rate that will minimize transformation of austenite to ferrite or pearlite and yield the desired amount of martensite or bainite.

The interface heat transfer coefficient is defined as:

$$h = \frac{q}{A\,(T_1 - T_2)} \qquad \textbf{(Eq 1)}$$

where h is the interface heat transfer coefficient; q is the heat flow from the part to the quenchant; A is the part area; T_1 is the part surface temperature; and T_2 is the bath temperature.

A similar ratio, more widely used in steel quenching, is the Grossmann number (H) defined by the following equation:

$$H = \frac{h}{2k} \qquad \textbf{(Eq 2)}$$

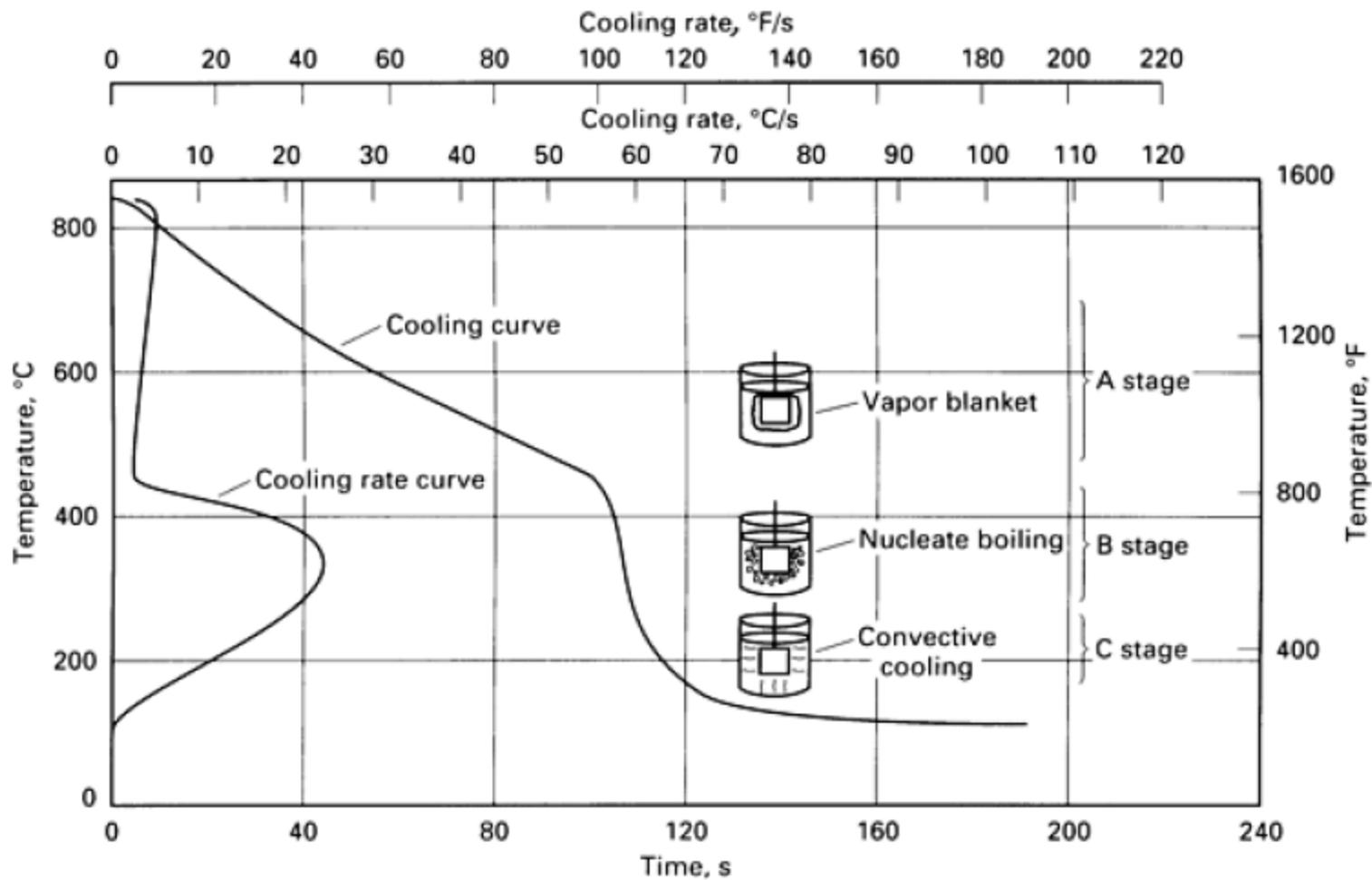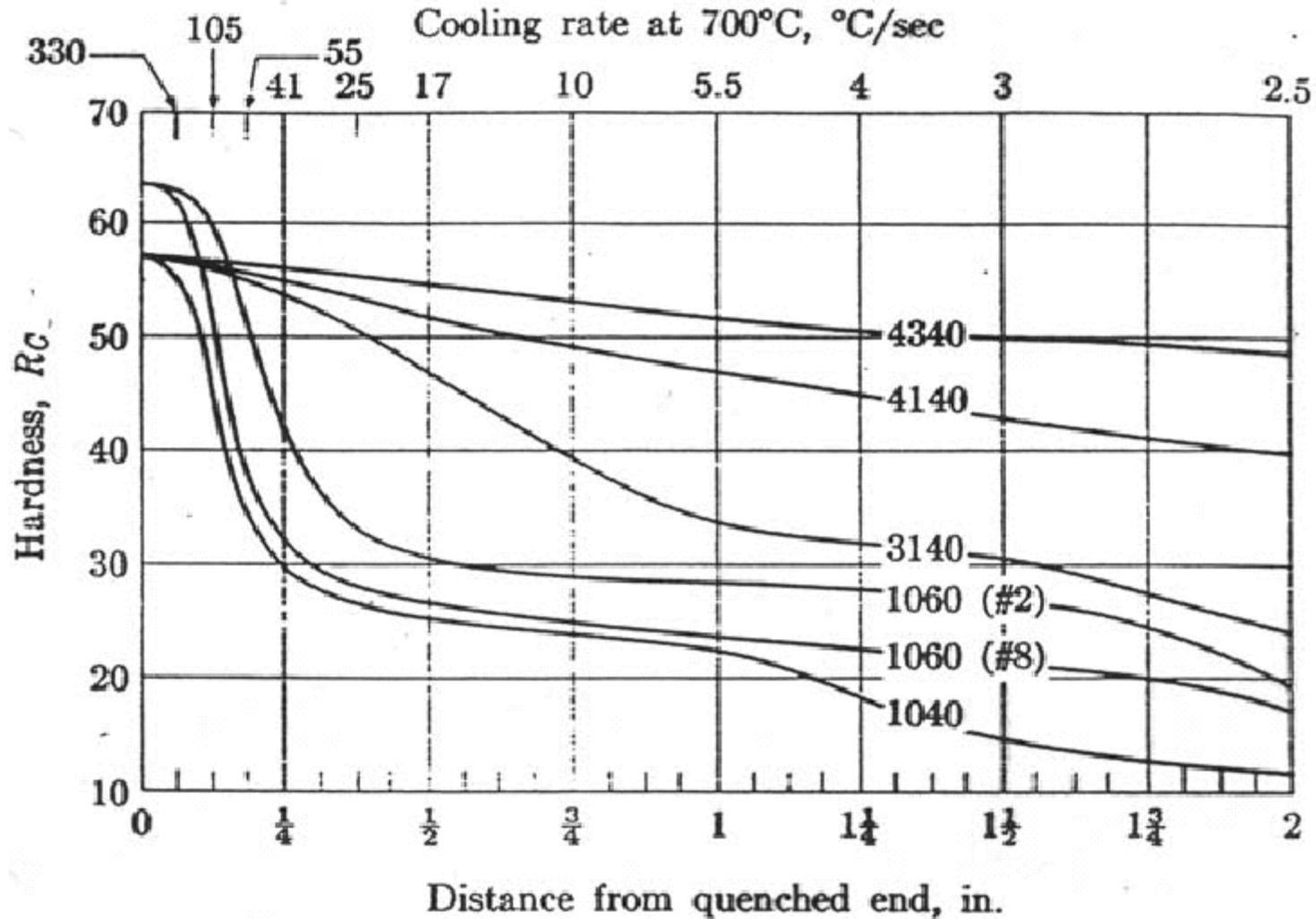where k is the conductivity of the metal.

Fig. 2 Cooling curve and cooling rate curve at the center of a 25 mm (1.0 in.) diameter probe quenched with 95 °C (200 °F) water flowing at 15 m/min (50 ft/min)

Hardenability of 6 steels

45

Pearlite after a deep etching 4 min in 5% Nital. The micrograph from a scanning electron microscope shows the gray cementite plates. Ferrite between cementite plates is dissolved by etching.
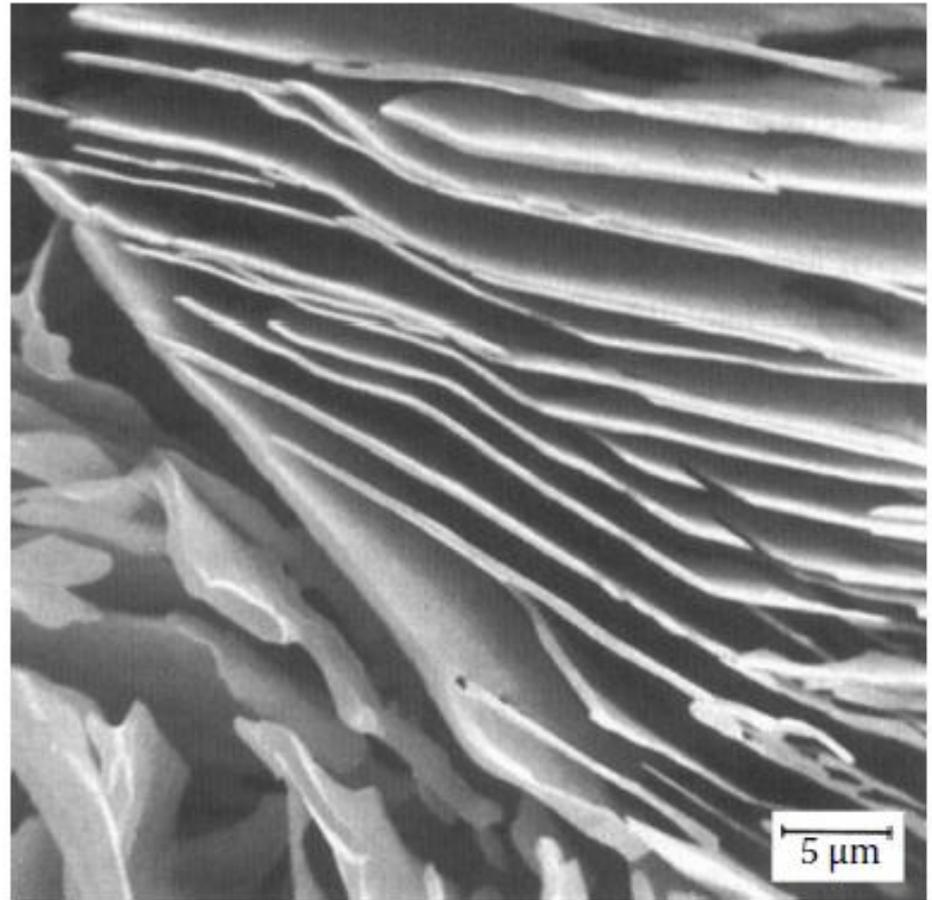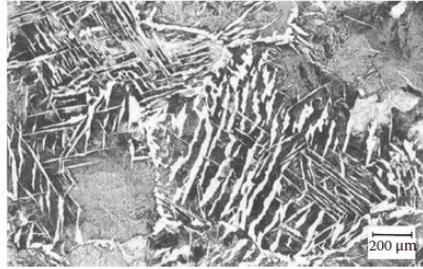
FIGURE 1.10
Ferrite in Widmannstätten arrangement and pearlite. Steel with 0.45 wt.% C. Heat treatment: 1000°C 15 min continuous cooling from 800°C to 500°C in 100 s.
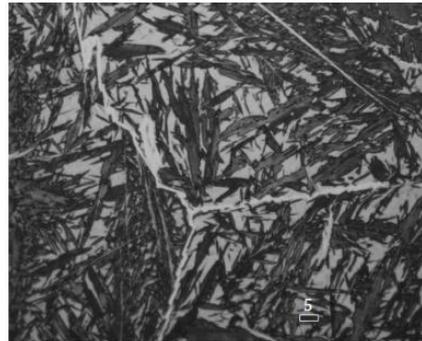

FIGURE 1.11
Microstructure of improperly carburized SAE 9310 alloy steel (Fe–0.1% C–0.55% Mn–3.25% Ni–1.2% Cr–0.12% Mo) tint etched with Beraha's reagent (100 mL water–10 g $Na_2S_2O_3$–3 g $K_2S_2O_5$). Carburizing treatment: 954°C (1750°F)—11 h, air cool. Note the complete coverage of the prior-austenite grain boundaries with proeutectoid cementite. Plate martensite was colored blue and brown, retained austenite is cream colored. Some bainite was observed. (Courtesy of G.F. Vander Voort.)
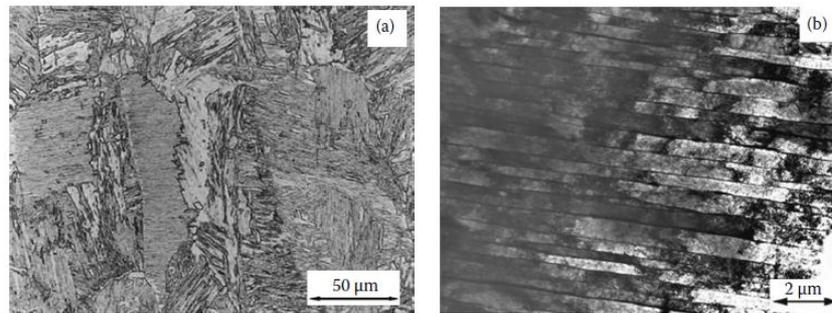

FIGURE 1.12
(a) Lath martensite in a low-carbon steel attained by rapid cooling in a weld. (b) Micrograph from transmission electron microscope of the same structure exhibiting parallel and long lath martensite plates with high dislocation density. (Adapted from Totten, G., *Steel Heat Treatment: Metallurgy and Technologies*, Taylor & Francis Group LLC, Boca Raton, FL, 2006.)
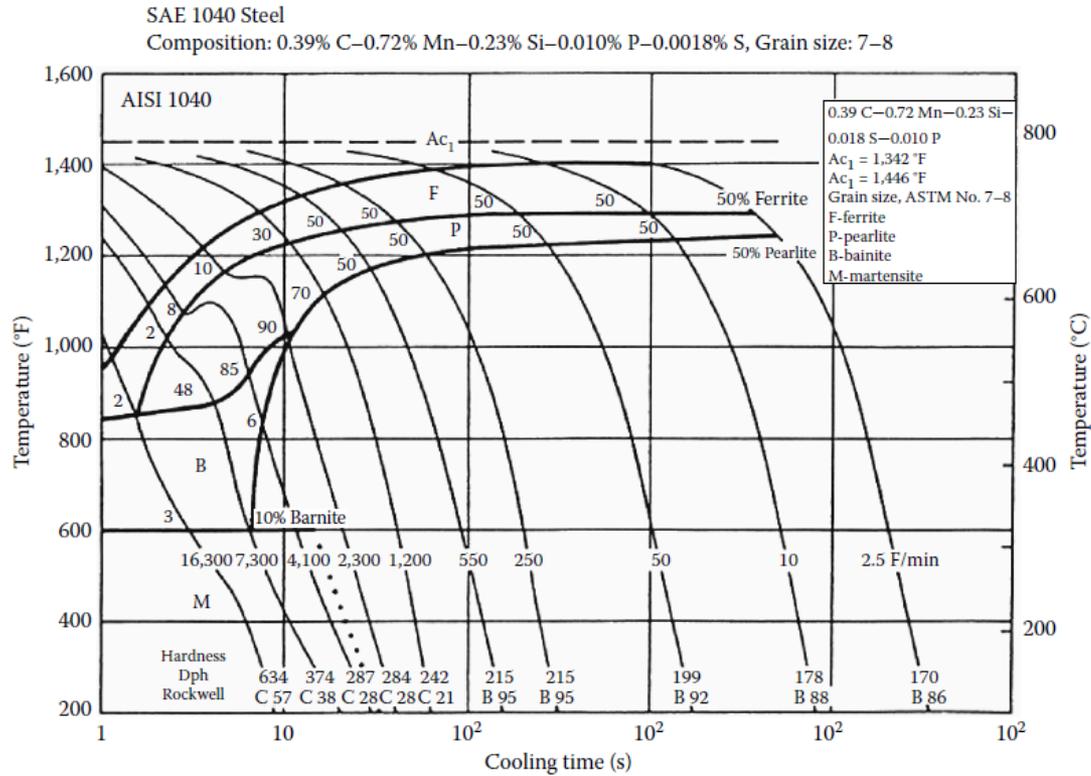
CCT Diagram for SAE 1040 Steel

FIGURE 1.17
CCT diagram for an unalloyed steel (AISI 1040). (From Totten, G., *Steel Heat Treatment: Metallurgy and Technologies*, Taylor & Francis Group LLC, Boca Raton, FL, 2006. With permission.)
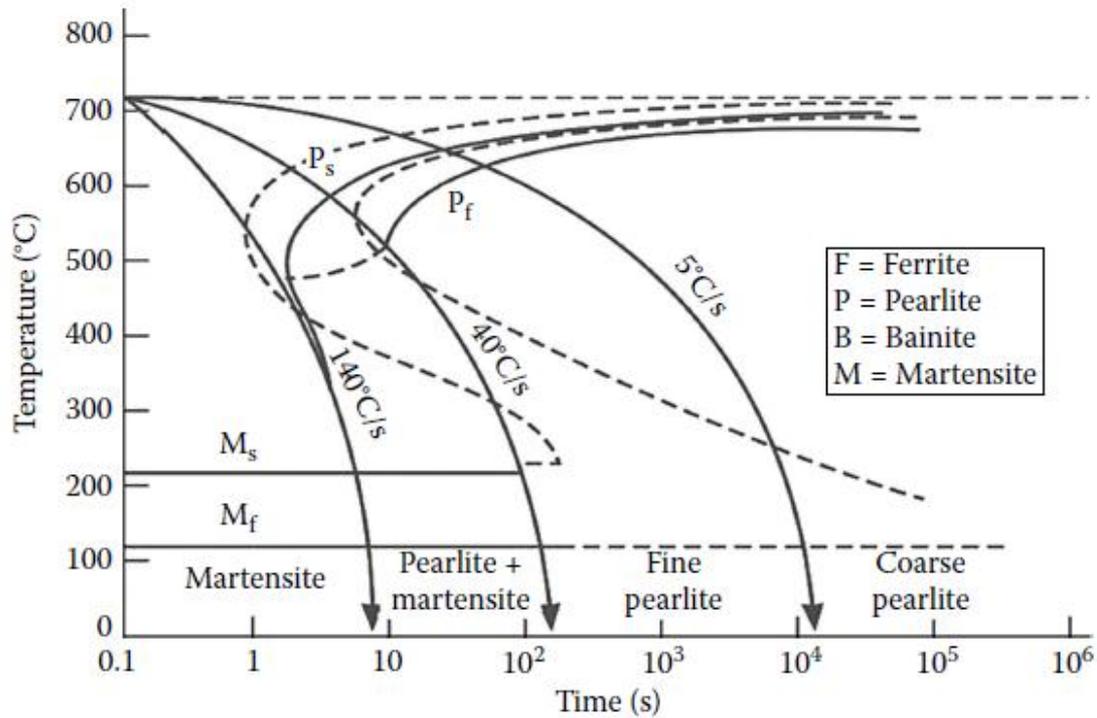
FIGURE 1.20
CCT curve (solid lines) and IT curve (dashed lines) both for SAE 1080 steel. (Adapted from Askeland, D.R., *The Science and Engineering of Materials*, 4th ed., PWS Publishing Company, Boston, MA, 1989.)
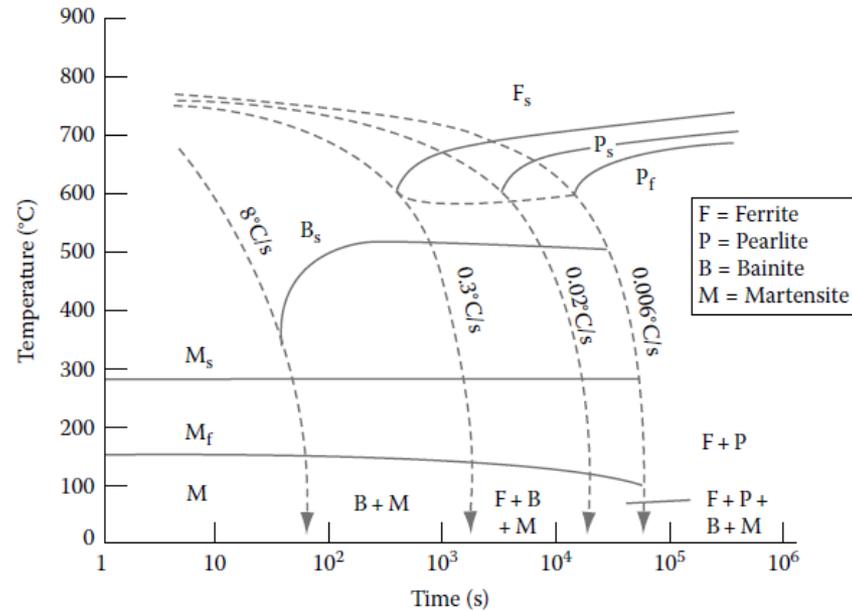
CCT Diagram SAE 4340

FIGURE 1.21
CCT curve for SAE 4340 steel. (Adapted from Askeland, D.R., *The Science and Engineering of Materials*, 4th ed., PWS Publishing Company, Boston, MA, 1989.)

Figure 1.21 is a CCT curve for SAE 4340 steel. In this last type of steel, even for relatively low cooling rate it is possible to obtain martensite as microstructure. Among these steels, SAE 4340 has the highest hardenability [30].

Parameters influencing Hardenability

1	The chemical composition (carbon + other elements) *- increasing wt.%C increases hardenability* *- of the common alloying elements, only Co is known to decrease hardenability*
2	The austenite grain size at the instant of quenching *- the larger the grain, the better (due to reduction in pearlite nucleation sites).*
3	

Nature of Alloying Additions

Austenite-Forming Elements

- The most important austenite-forming elements are carbon, nickel, and manganese. If sufficient quantities are used, steels that are austenitic even at room temperature may be produced. Austenite-forming elements perform by increasing the temperature at which austenite exists by raising the A_4 temperature (the temperature of formation of austenite from the liquid phase) and decreasing the A_3 temperature [10,11]. Typically, they possess the same crystal structure as the FCC austenite.

Ferrite-Forming Elements

- Ferrite-forming elements stabilize ferrite by decreasing the temperature range in which austenite exists by lowering the A_4 temperature and increasing the A_3 temperature. They function by reducing the solubility of carbon in austenite, which increases the concentration of carbides in the steel. Ferrite-forming elements include chromium (Cr), tungsten
- (W), molybdenum (Mo), vanadium (V), aluminum (Al), and silicon (Si). Ferrite-forming elements have the same crystal structure as that of the BCC ferrite [10].

Carbide-Forming Elements

- The presence of hard carbides increase steel hardness, strength, and wear resistance. Carbide forming elements include (with increasing affinity for carbon): chromium, tungsten, molybdenum, vanadium, titanium, niobium, tantalum, and zirconium. Some ferrite-forming elements may also promote carbide formation. Non-iron carbides that are formed include Cr_7C_3, W_2C,
- VC, Mo_2C as well as complex carbides such as Fe_4W_2C. High-speed and hot-work tool steels normally contain three types of carbides: M_6C, $M_{23}C_6$, and MC. The letter M represents collectively all the metal atoms [11]. All carbide-forming elements are also nitride formers.
- Alloying elements such as nickel, silicon, cobalt, aluminum, copper, and nitrogen do not form carbides. Therefore, they can only be present in steel as a solid solution with iron.
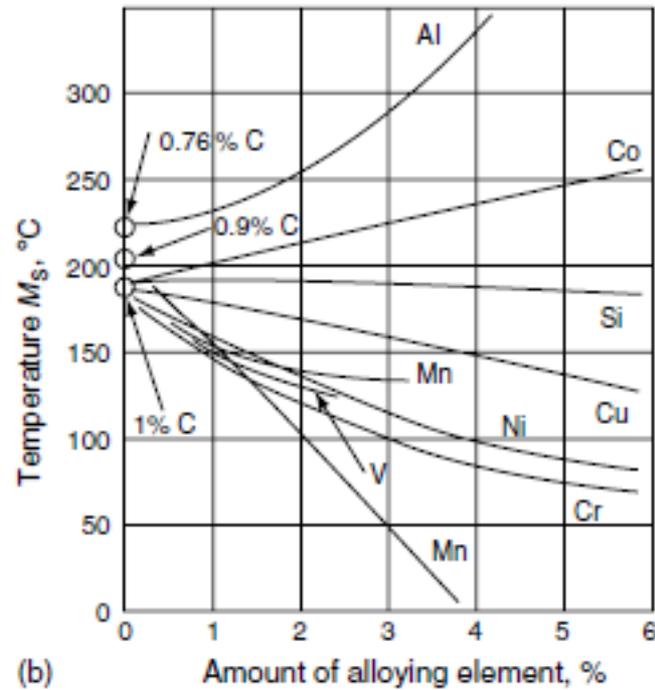
Effect of Alloying on Ms Temperature

FIGURE 4.8 The influence of the content of (a) carbon and (b) alloying elements at 1% C on the martensite point position.
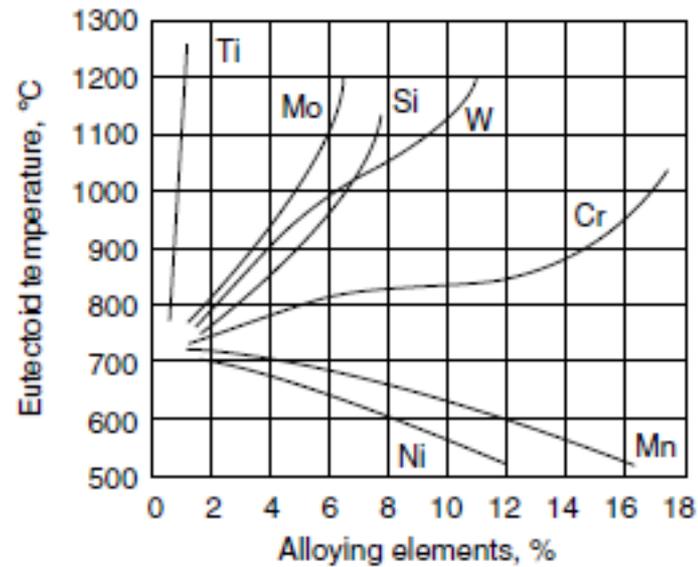
Effect of Alloying on Eutectoid Temeperature

FIGURE 4.5 Effect of alloying elements on the eutectoid transformation temperature A_{c1}.
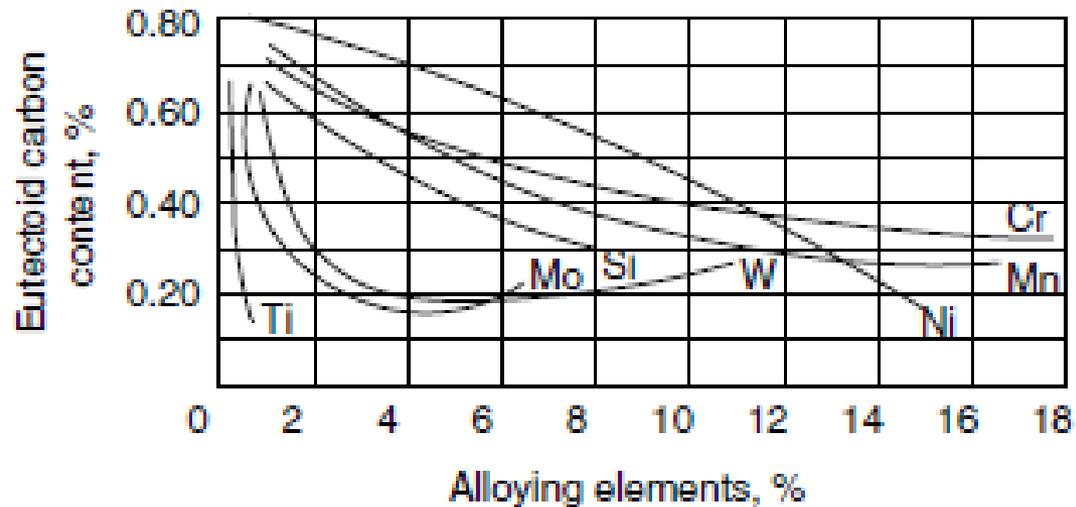
Effect of Alloying on Eutectoid Carbon

FIGURE 4.6 Effect of alloying elements on the concentration of carbon in eutectoid.
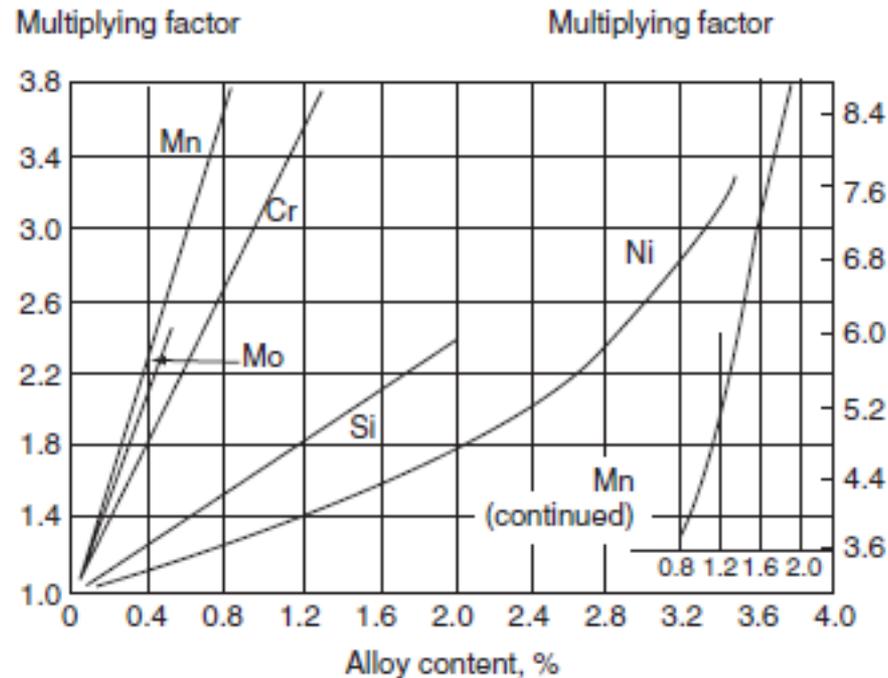
Effect of Alloying on Hardenability

FIGURE 5.8 Multiplying factors for different alloying elements when calculating hardenability as D_I value, according to AISI. (From K.E. Thelning, *Steel and Its Heat Treatment*, 2nd ed., Butterworths, London, 1984, p. 145.)
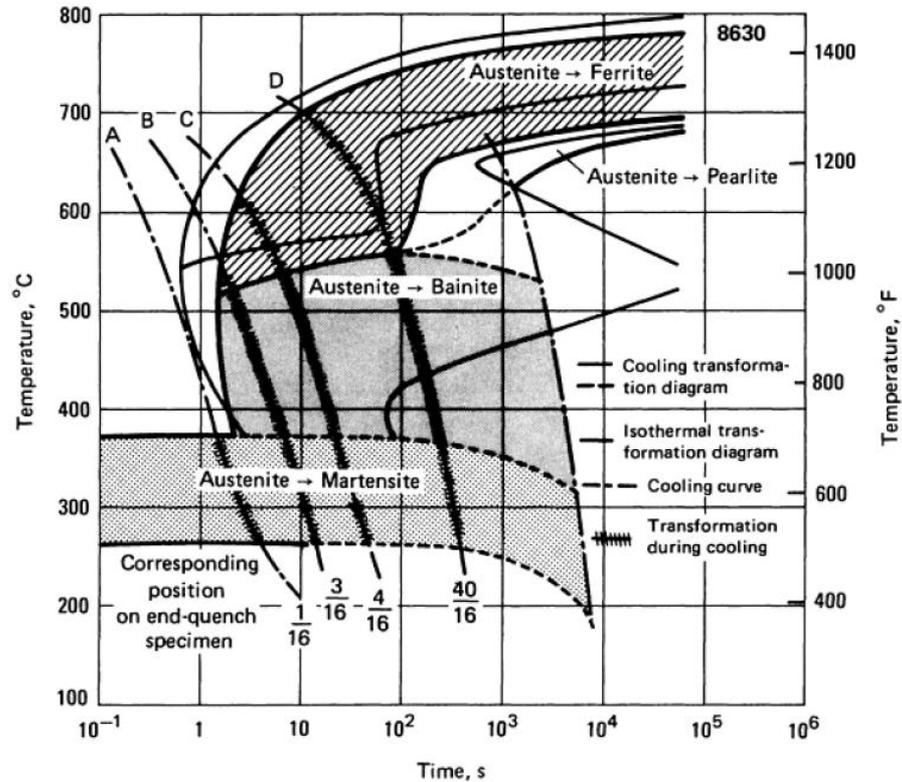
TTT Diagram of SAE 8630

Fig. 29 Transformation diagrams and cooling curves for 8630 steel, indicating the transformation of austenite to other constituents as a function of cooling rate
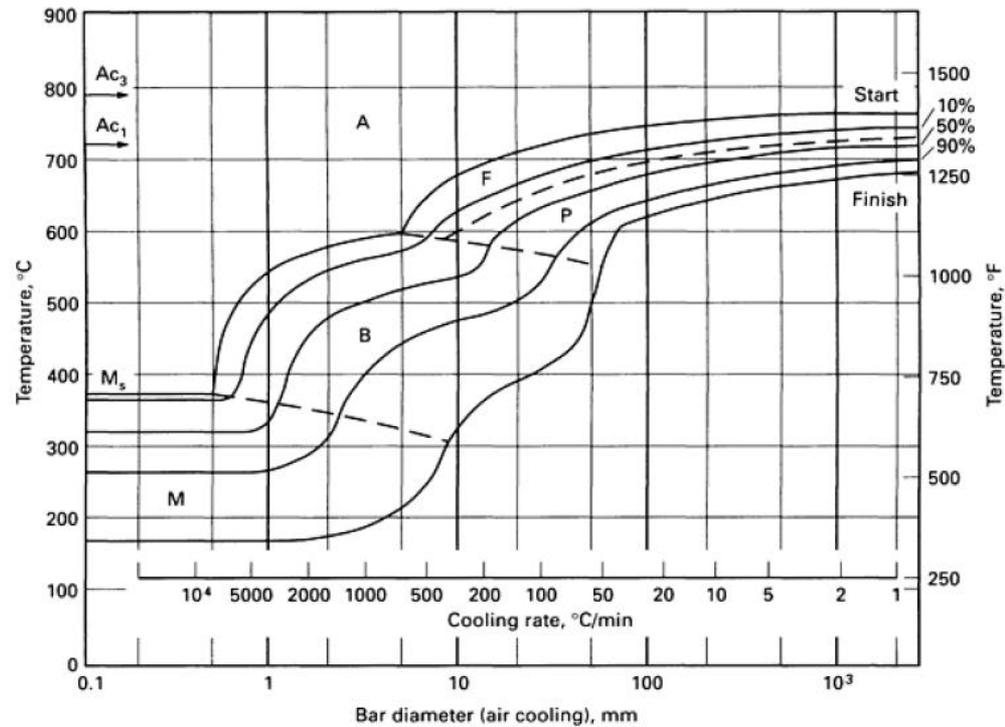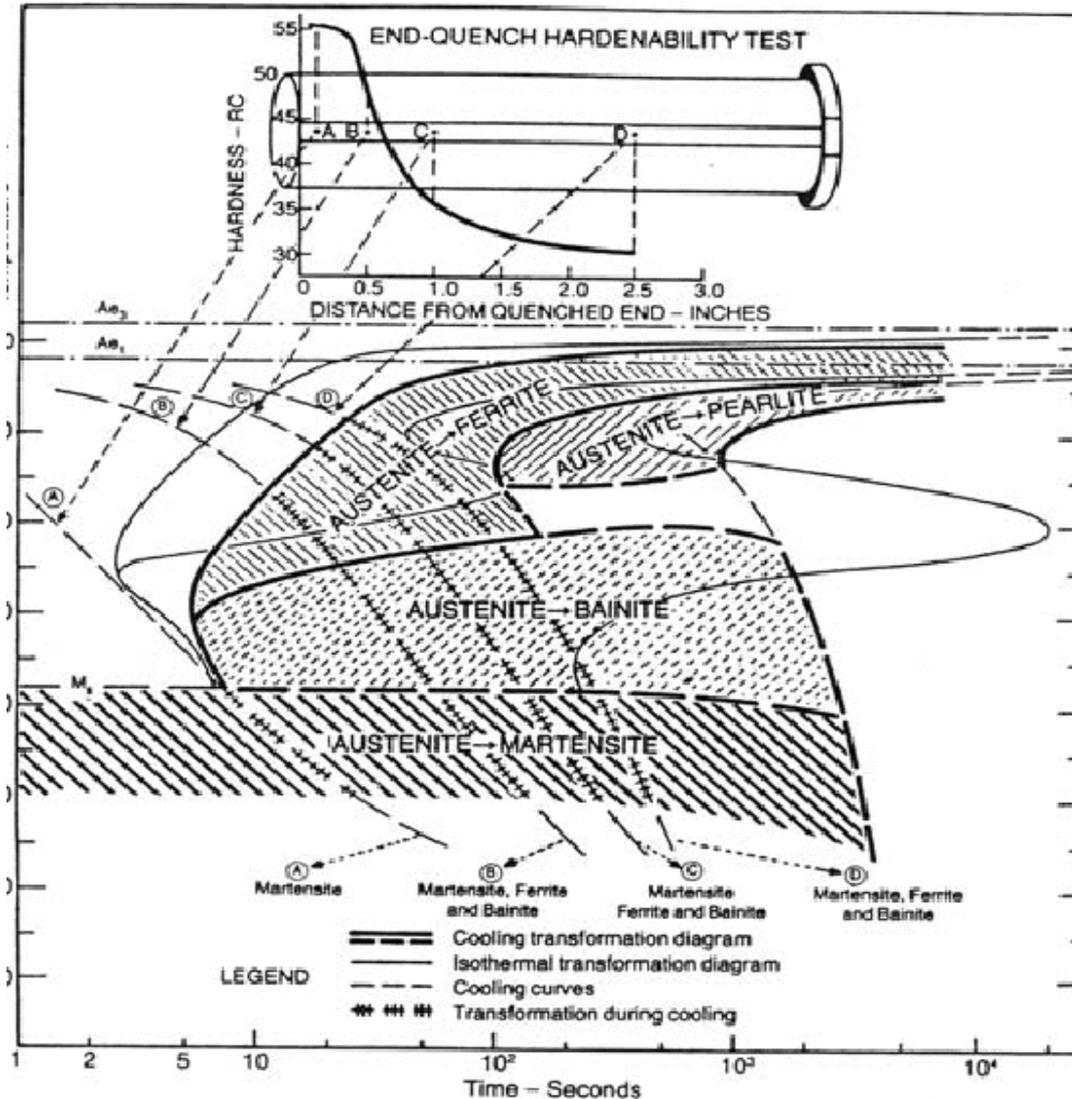
CCT Diagram of SAE 4310

Fig. 36 CCT diagram for 4130 low-alloy steel with 0.30C-0.25Si-0.50Mn-0.020P-0.020S-1.00Cr-0.20Mo composition tested at 750 °C (1380 °F). Calculated critical cooling rate is 143 °C/s (258 °F/s).
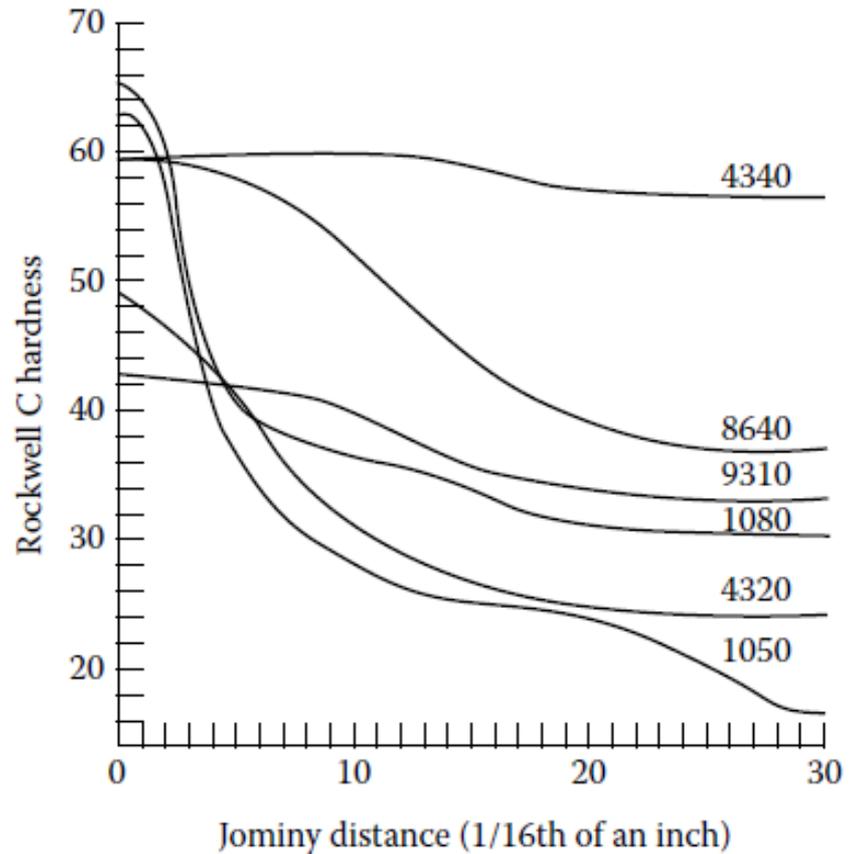
Jominy Hardenability and Microstructure

Hardenability of various steels

Jominy curve comparison of the hardenability of different steels, alloyed and unalloyed.
(From Askeland,D.R., *The Science and Engineering of Materials*, 4th ed., PWS Publishing Company, Boston, MA, 1989. With permission.)

Effect of Carbon on max. hardness

As-quenched hardness as a function of the carbon content and martensite percentage in the microstructure.

(From ASM, Properties and selection—Irons, steels and high performance alloys, in *ASM Handbook*,)
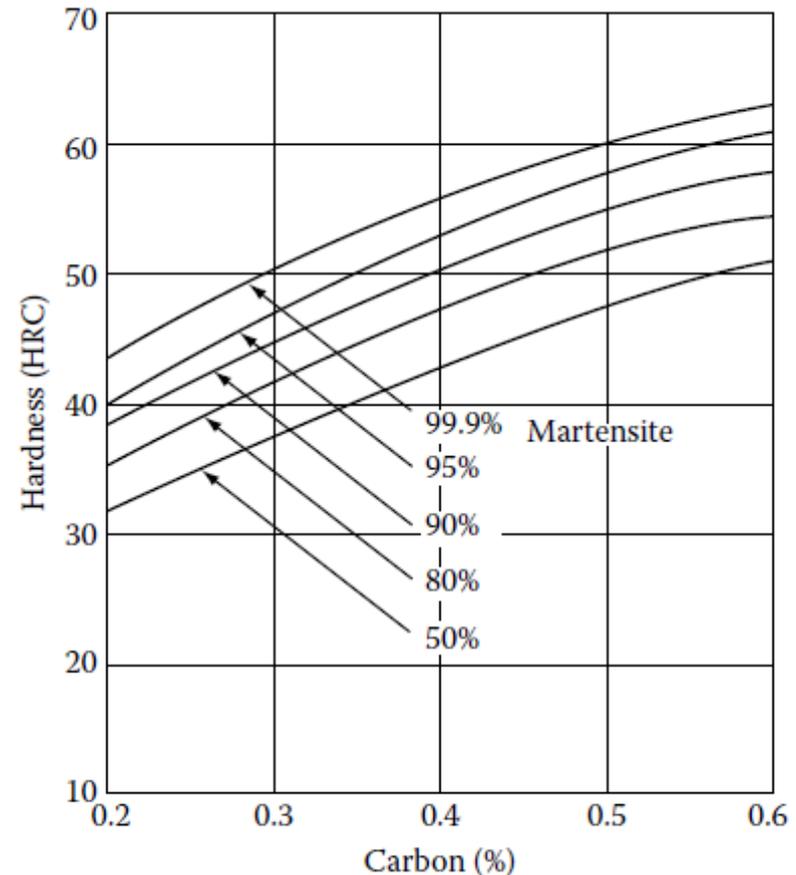
Tempering

- Martensite is very hard and brittle.

- Tempering is applied to hardened steel to reduce brittleness, increase ductility, and toughness and relieve stresses in martensite structure.

- In this process, the steel is heated to lower critical temperature keeping it there for about one hour and then cooled slowly at prescribed rate.

- This process increses ductility and toughness but also reduces hardness, strength and wear resistance marginally. Increase in tempering temperature lowers the hardness.
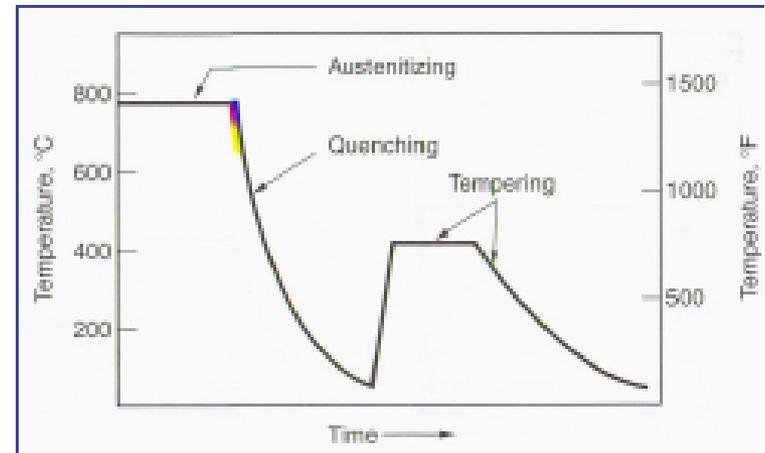
Stages of Tempering

Tempering is a process in which the microstructure approaches equilibrium under the influence of thermal activation. It follows that the tendency to temper depends on how far the starting microstructure deviates from equilibrium .	
Stage 1: Upto 250°C	• In high-carbon steels, the precipitation of excess carbon begins with the formation of a transition carbide, such as $\sum$(Fe2C4). A fine adjustment between the carbides $\sum$ and the ferrous structure is attributed to a precipitation hardening effect of martensite in high C steels tempered between 50°C and 100°C of temperature.
Stage 2 200°C–300°C	• Tempering at higher temperatures, in the range for 1 h induces the retained austenite to decompose into a mixture of cementite and ferrite. When the austenite is present as a film, the cementite also precipitates as a continuous array of particles that have the appearance of a film . The martensite of the steels with less than 0.5% of carbon content has a retained austenite amount lower than 2%, reaching 6% for 0.8% of carbon.
Stage 3: 250°C–400°C	• Tempering at even higher temperatures leads to a coarsening of the cementite particles, with those located at the plate boundaries growing at the expense of the intra-plate particles. This precipitation is responsible for the embrittlement phenomenon can be avoided by Si addition, because it is an element insoluble in cementite, just allowing the cementite formation at temperatures where the Si diffusion occurs. This is considered a slow process because this alloy element is substitutional. • Cementite can also be observed during quenching when the Ms temperature is elevated, as it is the case of steel with low C content, mainly in the martensite formed right below Ms temperature. This phenomenon is known by self-tempering [53].
Stage 4:	• In carbon steels, the stage 3 marks the end of the tempering process, except if the sample is tempered for a long time or if the tempering temperature is excessively high. When this occurs, there is a growth process for cementite that corresponds to carbide coalescence, • a phenomenon that is sometimes called stage 4 of tempering [56].

Hardness reduction during tempering
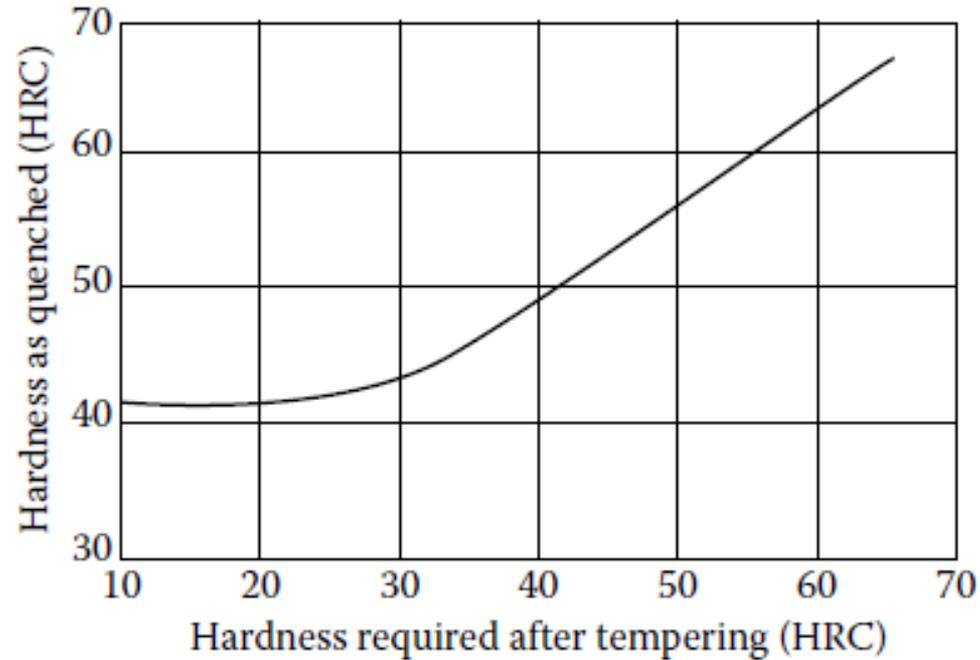
- **FIGURE 1.30**
- As-quenched minimum hardness recommended as
- a function of the required hardness after tempering.
- (Adapted from Silva, A.L.V.C. and Mei, P.R., *Aços e Ligas*
- *especiais*, Edgard Blucher, Sao Paulo, Brazil, 2006.)
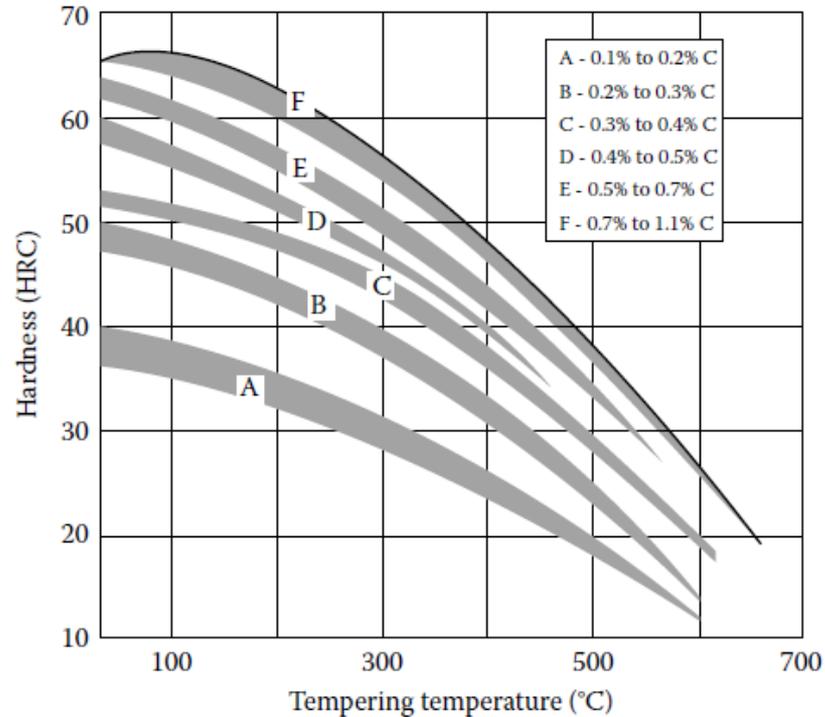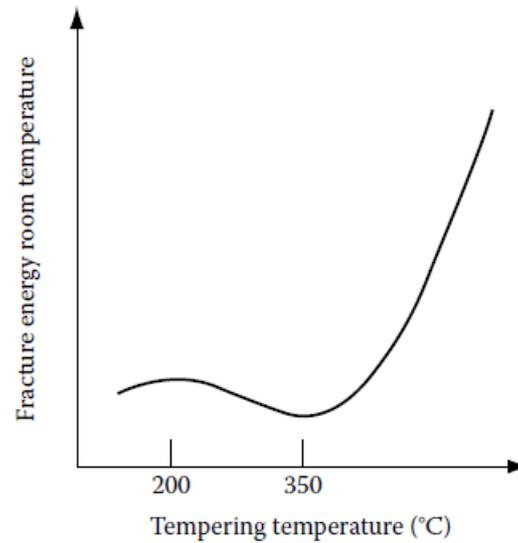
Effect of Tempering Temperature

FIGURE 1.32
Effect of carbon content in the hardness of tempered plain steels. (Adapted from Seco/Warwick, *Heat Treating Data Book*, 8th ed., Seco/Warwick Corporation, Meadville, PA, 2000, p. 96.)

Temper Embrittlement

- **FIGURE 1.36**
- Illustration of toughness loss after tempering in the embrittlement
- range. (Adapted from Nam, W. J. and Choi, H.C., *Mater.*
- *Sci. Technol.*, 15, 527, 1999.)
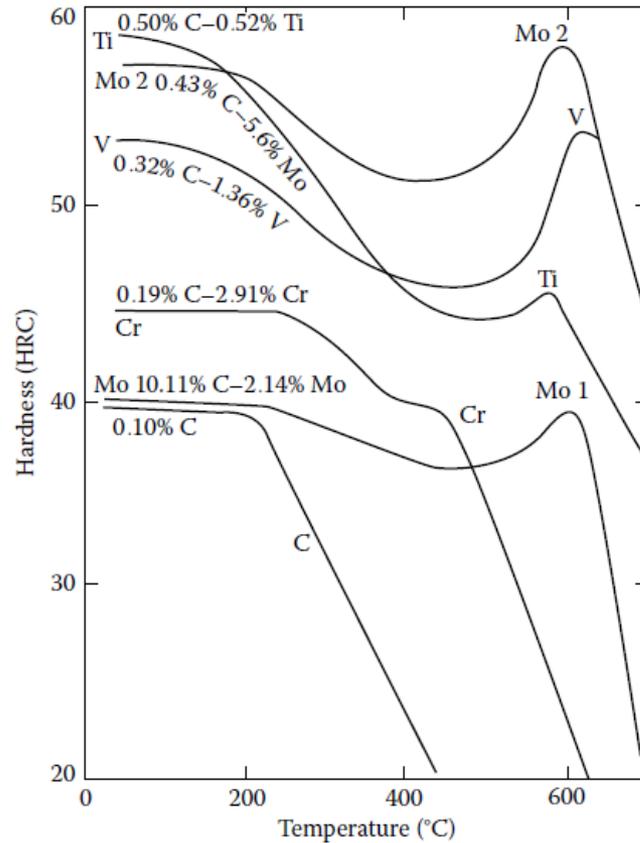
Secondary Hardening Effect

FIGURE 1.35
Effects of Ti, V, Cr, and Mo on the tempering hardness behavior. (Adapted from Bain, E.C. and Paxton, H.W., *Alloying Elements in Steel*, ASM, Metals Park, OH, 1966.)

Surface Hardening

◆ Heat treatment methods in general change the properties of entire material.

◆ Hardening improves wear resistance of material but lowers impact resistance and fatigue life. Therefore sometimes there is requirement of surface hardening

◆ Two methods are used, first is heating and cooing to get required phase, and second is thermo-chemical treatment.

- Induction heating
- Flame hardening
- High frequency resistance heating
- Laser beam hardening
- Electron beam hardening
- Carburizing
- Nitriding
- Cyanding