

Heat Treatment of Steels

Heat Treating – defined as the controlled heating and cooling of metals for the primary purpose of altering their properties (strength, ductility, hardness, toughness, machinability, etc)

Can be done for **Strengthening Purposes** (converting structure to martensite)

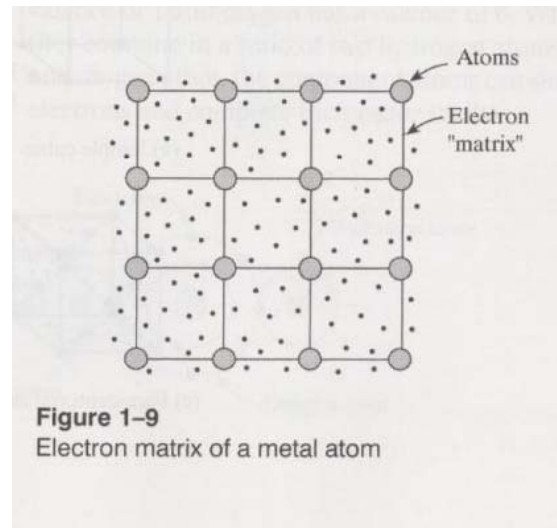
Can be done for **Softening and Conditioning Purposes** (annealing, tempering, etc.)

First, a basic review of metallurgy!

1.5 The Nature of Metals:

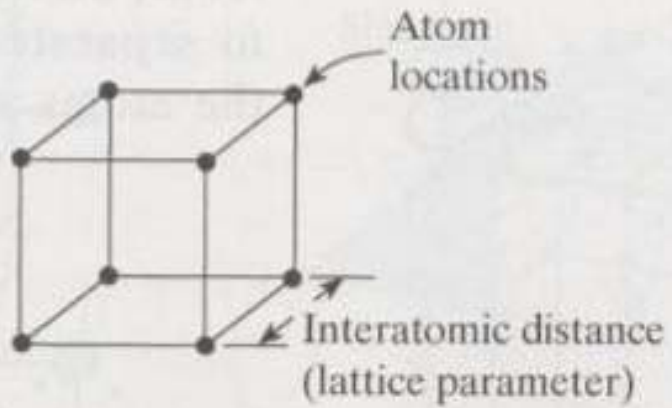
Characterized by:

1. Valence electrons of 1,2 or 3 – see periodic table
2. Primary bonding between electrons called *metallic bonding*:

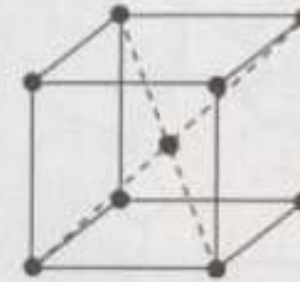


Valence electrons not "bonded" to particular atom but shared and free to drift through the entire metal

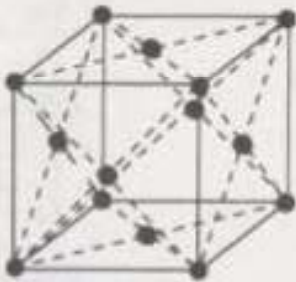
3. Properties include: good conductors of electricity and heat, not transparent, quite strong yet deformable!



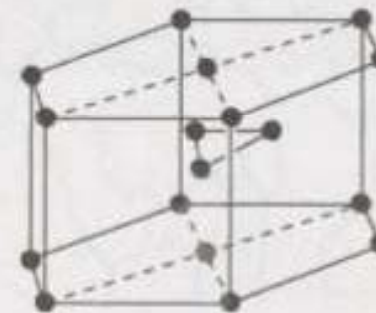
(a) Simple cubic



(b) Body-centered cubic



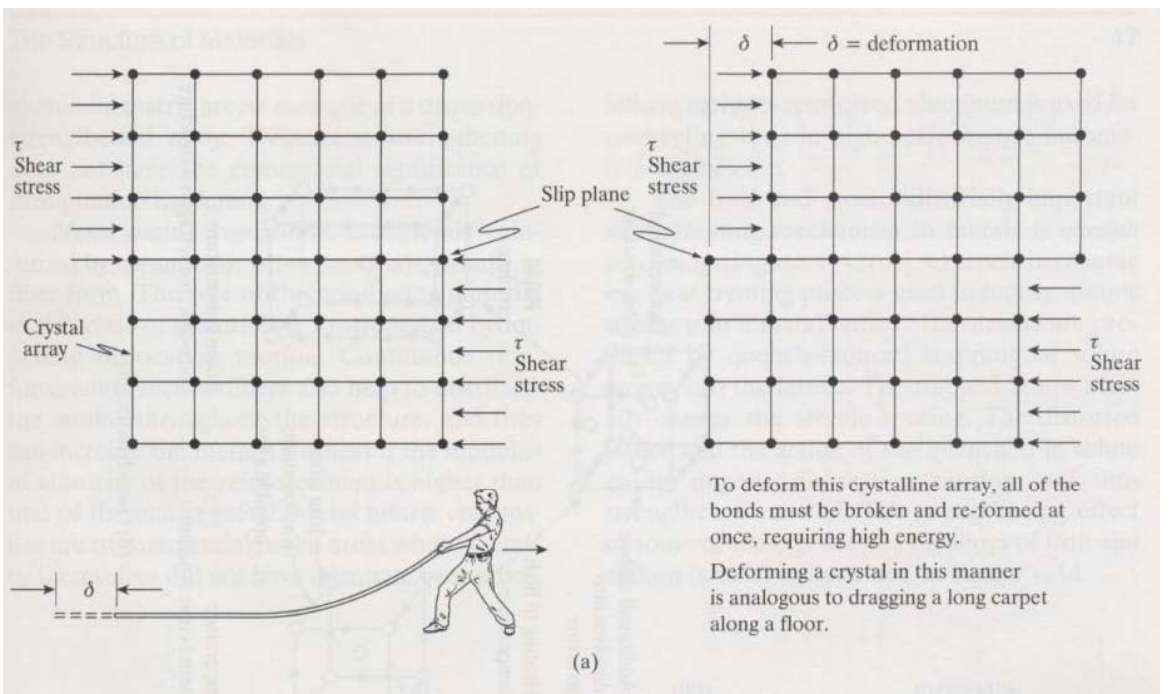
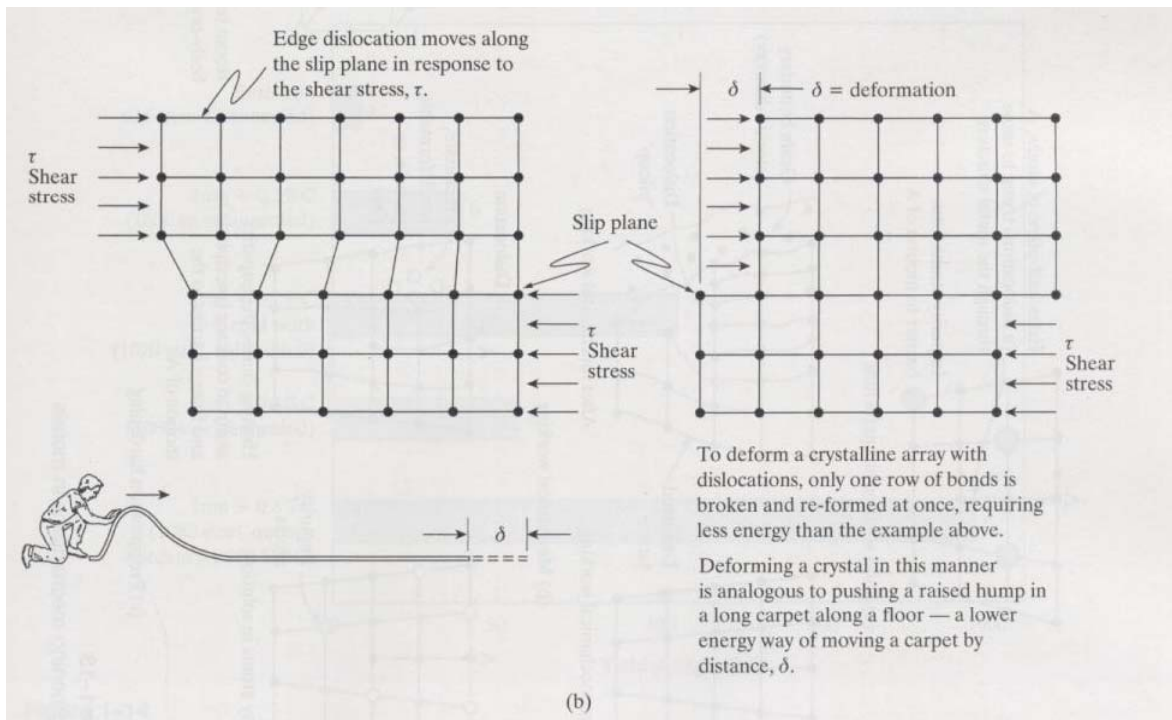
(c) Face-centered cubic



(d) Hexagonal close-packed

Crystalline structures (i.e. metals) atoms are arranged in unit cells – 4 common cells shown above

How do Metal Crystals Fail??
Answer: Slip due to dislocations



How does crystal Structure FCC, BCC, HCP effect:

- Strength??
- Ductility/Toughness??
- Stiffness??

Theoretical Strength of Metal

- Strength, S_u should be approximately $E/10$ if based on atomic bond.
- $E/10 = 3,000$ ksi for steel >>> actual S_u which is between approximately 30 ksi to 200 ksi
- Why?????
- DEFECTS!!!

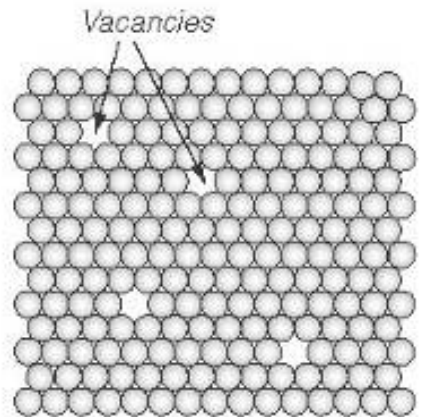
Types of Defects:

- Surface Defects
 - Grain boundaries
- Point Defects
 - Vacancy, **substitutional (atom replaces host), interstitial (atom squeezes in between host),** impurity
- Line Defects
 - Edge dislocations, screw dislocations

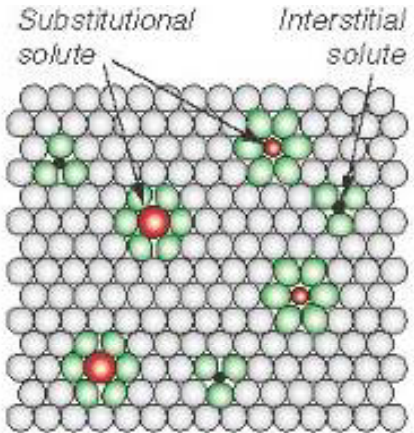


= good defect!

Little impact on strength



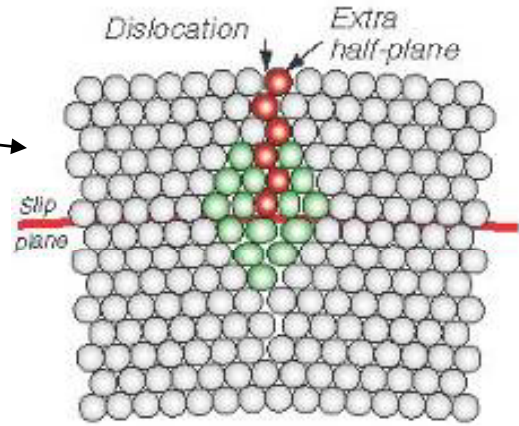
(a)



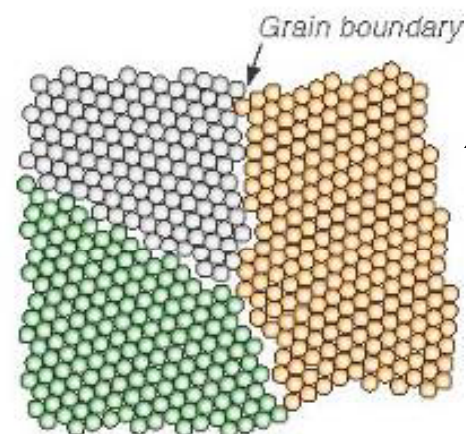
(b)

Alloying and heat treating

Greatest impact on strength and ductility!!



(c)



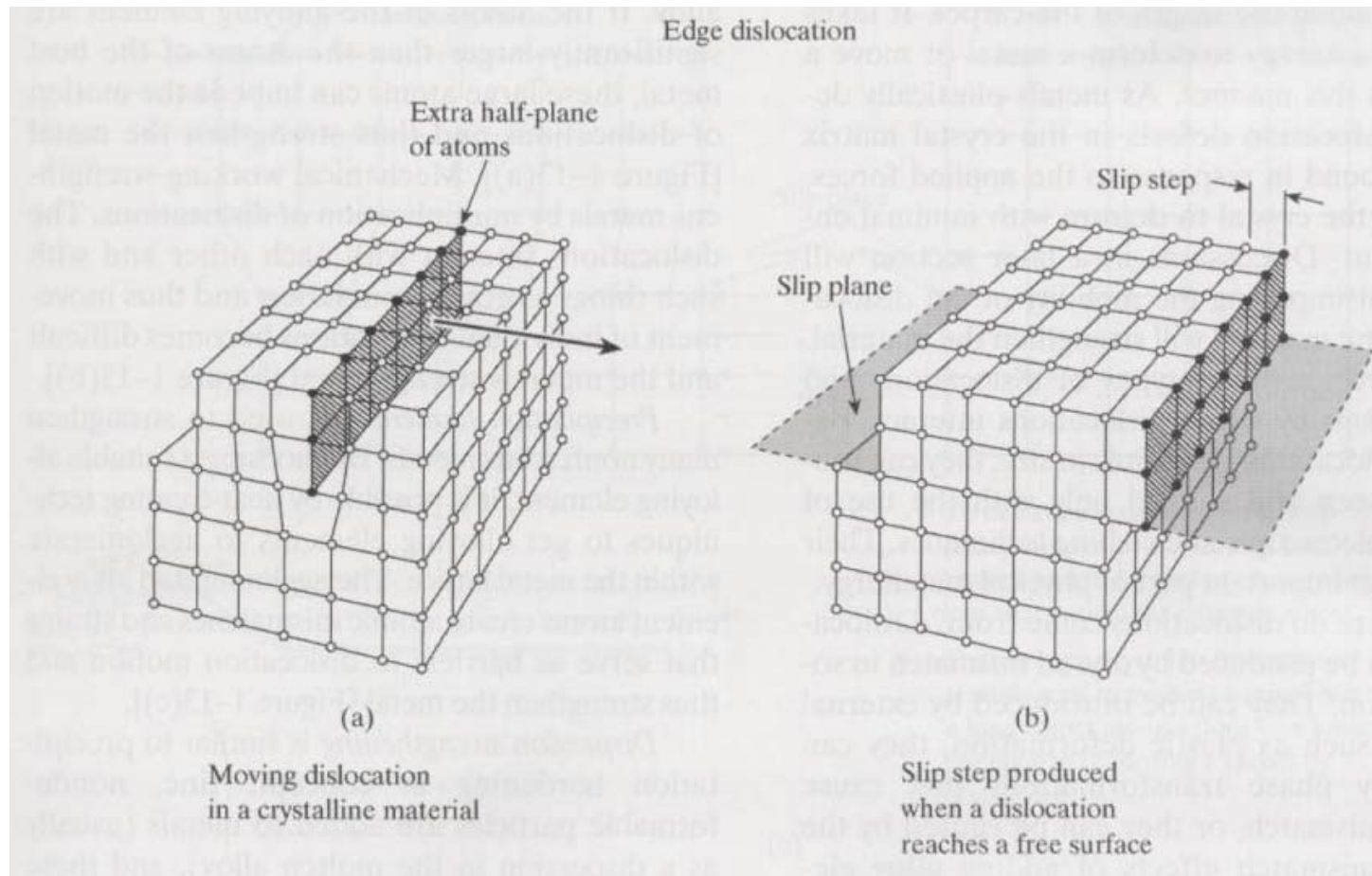
(d)

Course GB = weak, Fine GB = strong and ductile

Defects in crystals. (a) Vacancies—missing atoms. (b) Foreign (solute) atom on interstitial and substitutional sites. (c) Line Defect = A dislocation—an extra half-plane of atoms. (d) Grain boundaries.

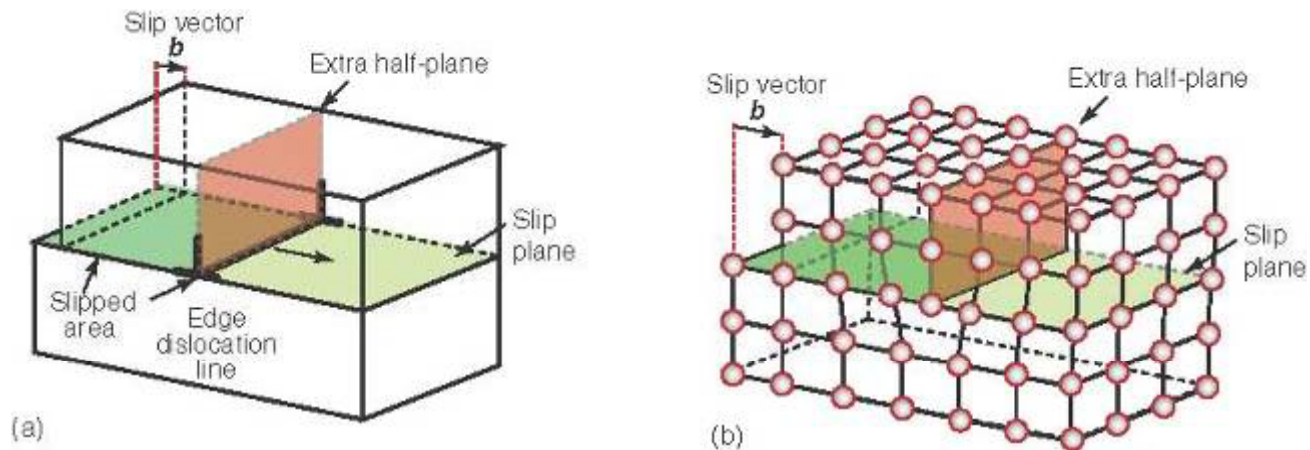
What is the most significant defect?

Answer: The line defect (edge dislocation or screw dislocation)



Line Defects – How metals fail:

Slip due to line defects (aka dislocations)



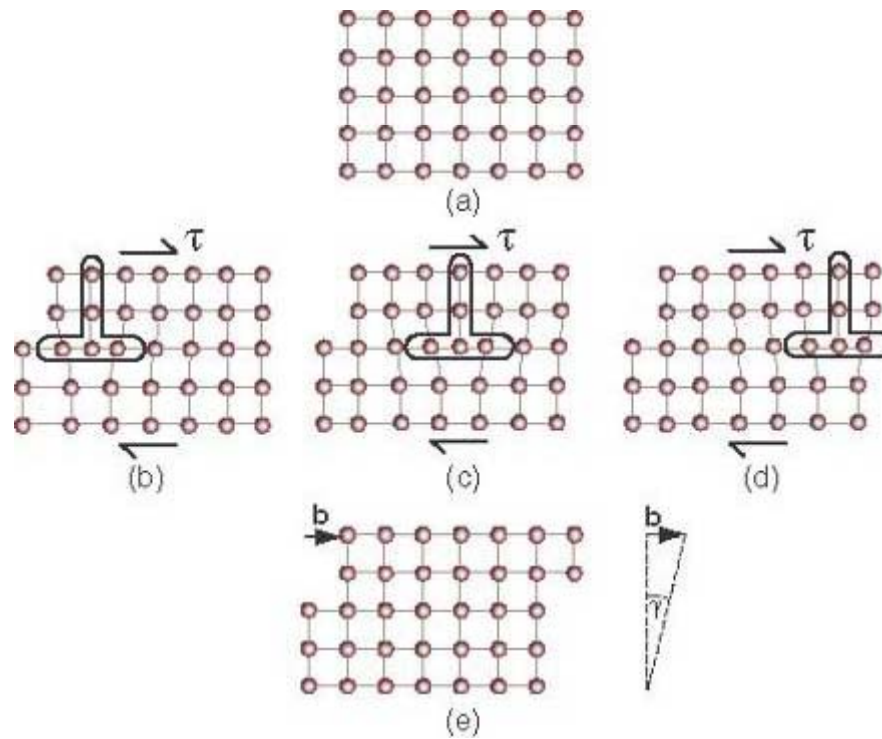
(a)

(b)

(a) Making a dislocation by cutting, slipping and rejoining bonds across a slip plane.

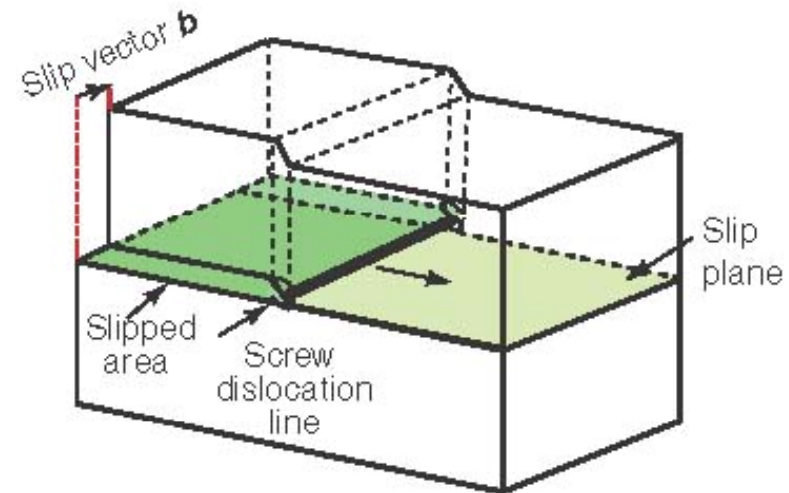
(b) The atom configuration at an edge dislocation in a simple cubic crystal. The configurations in other crystal structures are more complex but the principle remains the same.

Slip due to line defects (aka dislocations)

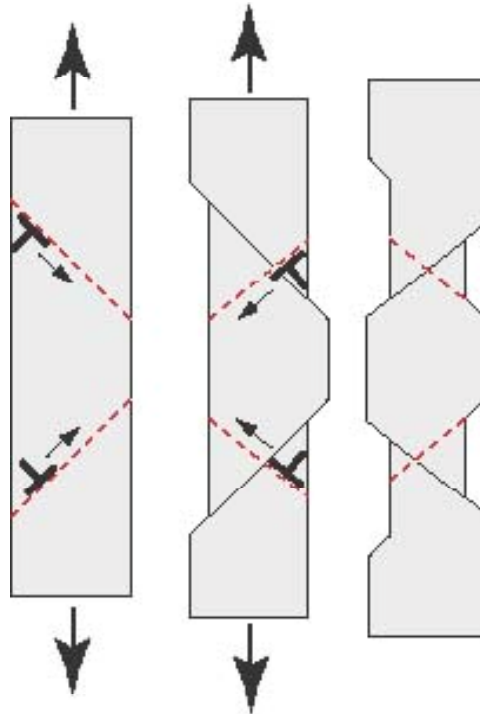


An initially perfect crystal is shown in (a). The passage of the dislocation across the slip plan, shown in the sequence (b), (c) and (d), shears the upper part of the crystal over the lower part by the slip vector b . When it leaves the crystal has suffered a shear strain γ .

A screw dislocation. The slip vector \mathbf{b} is parallel to the dislocation line $\mathbf{S}-\mathbf{S}$.



Millions of dislocations produce the noticeable “yield marks” seen below in a simple tensile specimen:



Dislocation motion causes extension

How to Strengthen Metals:

- **Key: prevent dislocations from moving through crystal structure!!!**
- Finer grain boundaries – can be done by recrystallizing (and cold working)
- Increase dislocation density via *COLD WORKING* (strain hardening)
- Add alloying elements to give –*SOLID SOLUTION HARDENING*.
- Add alloying elements to give precipitates or dispersed particles – *PRECIPITATION HARDENING (aka Heat Treat)*
- *DISPERSION HARDENING*– fine particles (carbon) impede dislocation movement.
 - Referred to as Quench Hardening, Austenitizing and Quench or simply “Heat Treat”.
 - Generally 3 steps: heat to austenite T, rapid quench, then temper.

Several cells form a crystal, if many crystals are growing in a melt at the same time, where they meet = grain boundary as shown below:

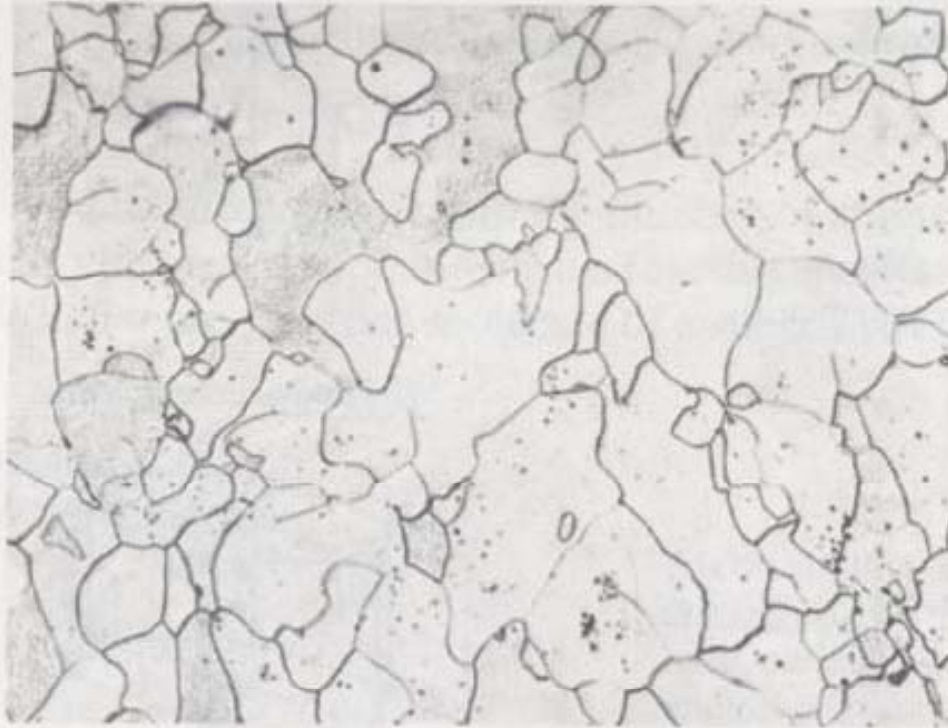


Figure 1-8
Microstructure of pure iron ($\times 100$). Dark areas are grain boundaries. Each grain is a crystal.

Mat'l constants

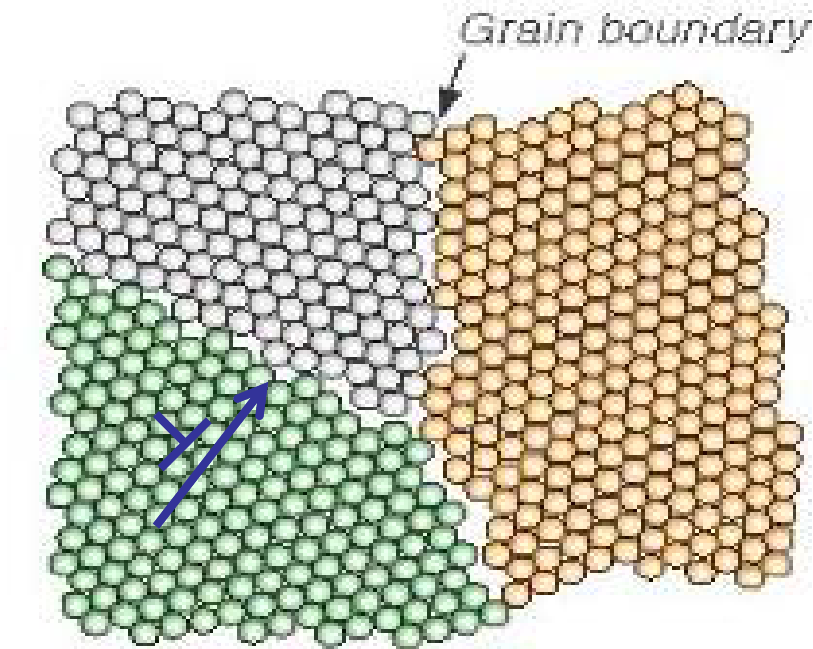
$$\sigma_y = \sigma_o + \frac{k_y}{\sqrt{d}}$$

Average grain diameter

Called Hall-Petch equation

The Effect of Grain Boundaries:

- Dislocations pile up at GB and can't go further – this effectively strengthens the crystal!



(d)


Work Hardening

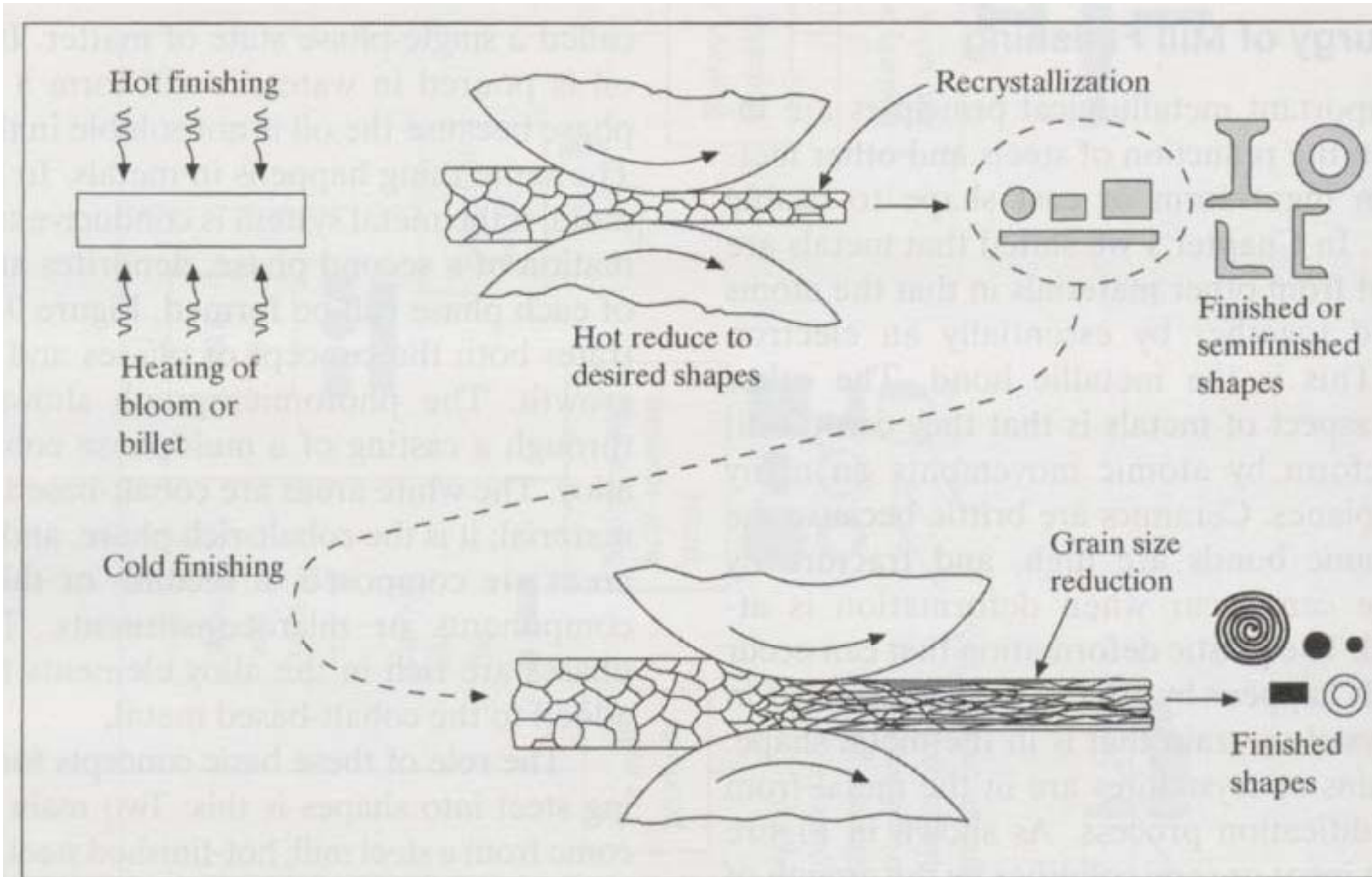
Work hardening, or strain hardening, results in an increase in the strength of a material due to plastic deformation.

Plastic deformation = adding dislocations – as dislocation density increases, they tend to “tie up” and don’t move.

Ludwik’s Equation:

Strain hardening index


$$\sigma = \sigma_y + K \epsilon_p^n$$



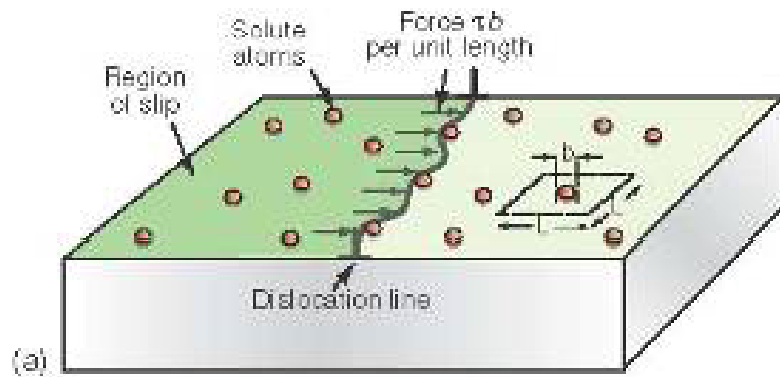
Hot finishing = 1

benefit

Cold finishing = 2

benefits

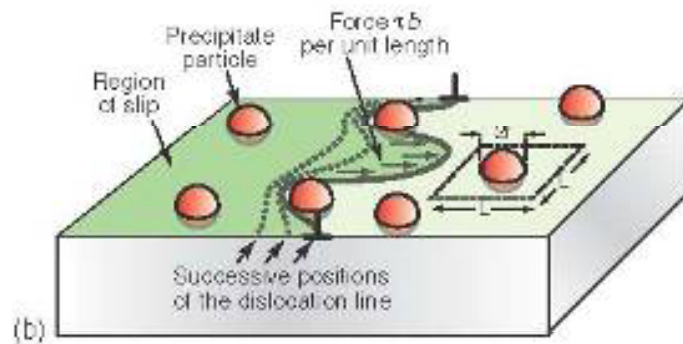
Solution Hardening (AKA Alloying):



= strengthening by deliberate additions of impurities (alloying elements) which act as barriers to dislocation movement.

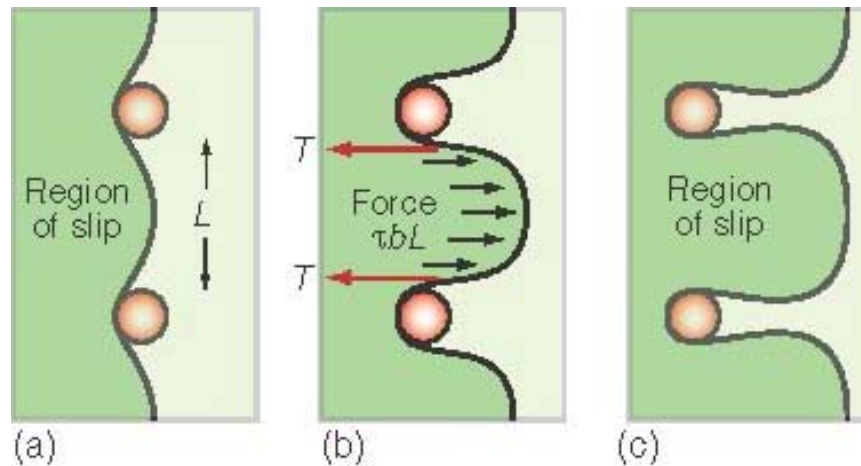
Example: addition of zinc to copper making the alloy brass (copper dissolves up to 30% zinc). Zinc atoms replace copper atoms to form random **substitutional** solid solution. The zinc atoms are bigger than copper and by squeezing into the copper lattice, they distort it making it harder for dislocations to move.

Dispersion and Precipitate Strengthening (aka Heat Treat):



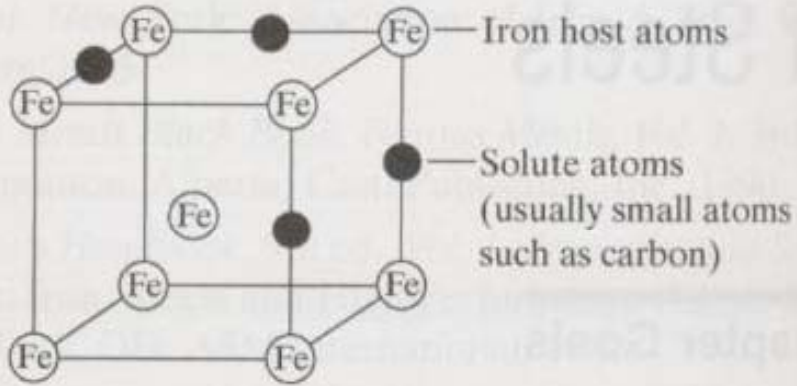
Disperse small strong particles (i.e. carbon) to impede dislocations

Dispersion and Precipitate Strengthening (aka Heat Treat):



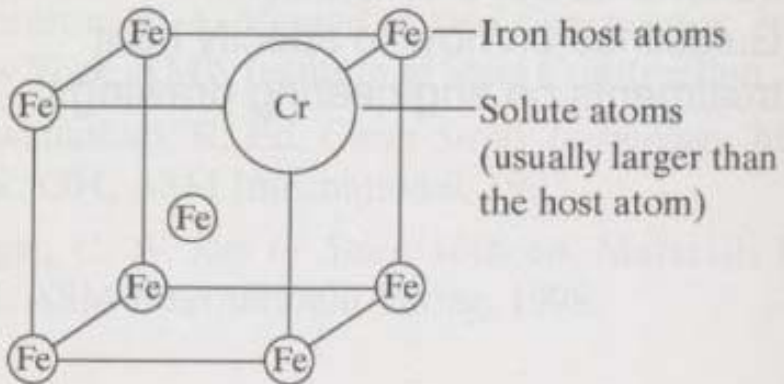
Successive positions of a dislocation as it bypasses particles that obstruct its motion.
The critical configuration is that with the tightest curvature, shown in (b).

1. Solute atoms located between the atoms of the host metal — an interstitial solution



← This is *dispersion and precipitate strengthening*

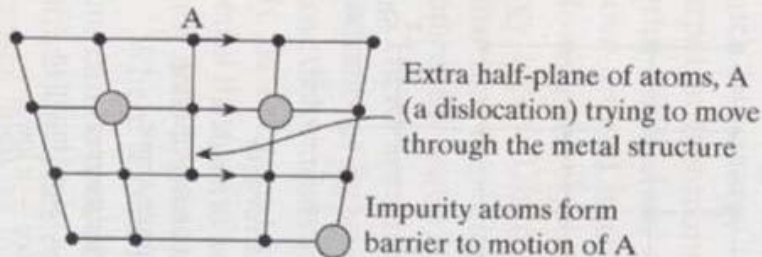
2. Solute atoms displacing atoms of the host metal — a substitutional solution



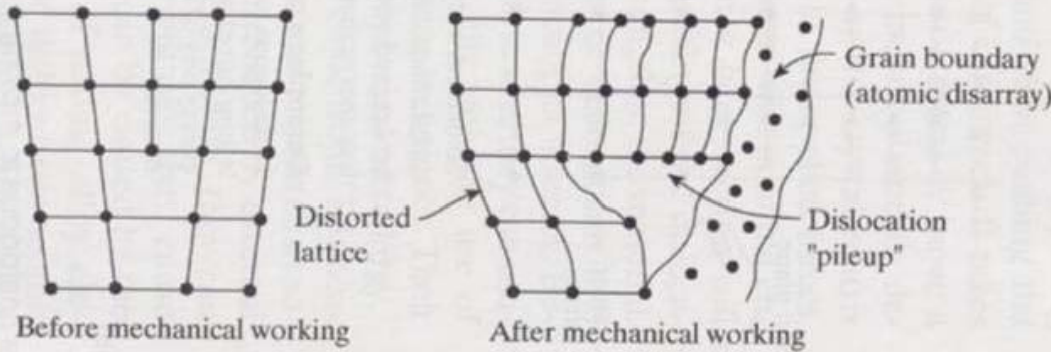
← This is *solution hardening (alloying)*

Figure 10-1
Interstitial and substitutional solid solution

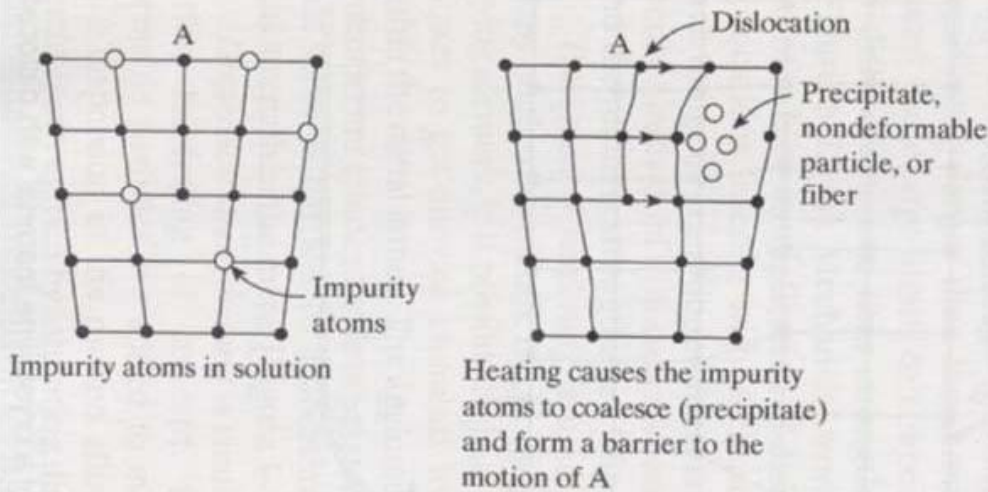
How to strengthen metals:



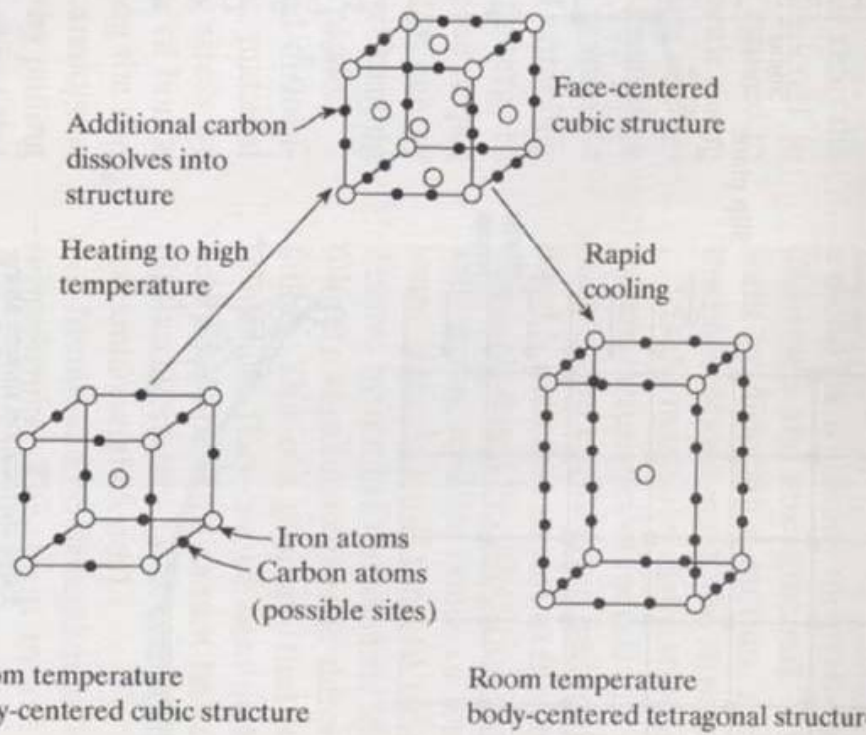
(a) Solid solution strengthening



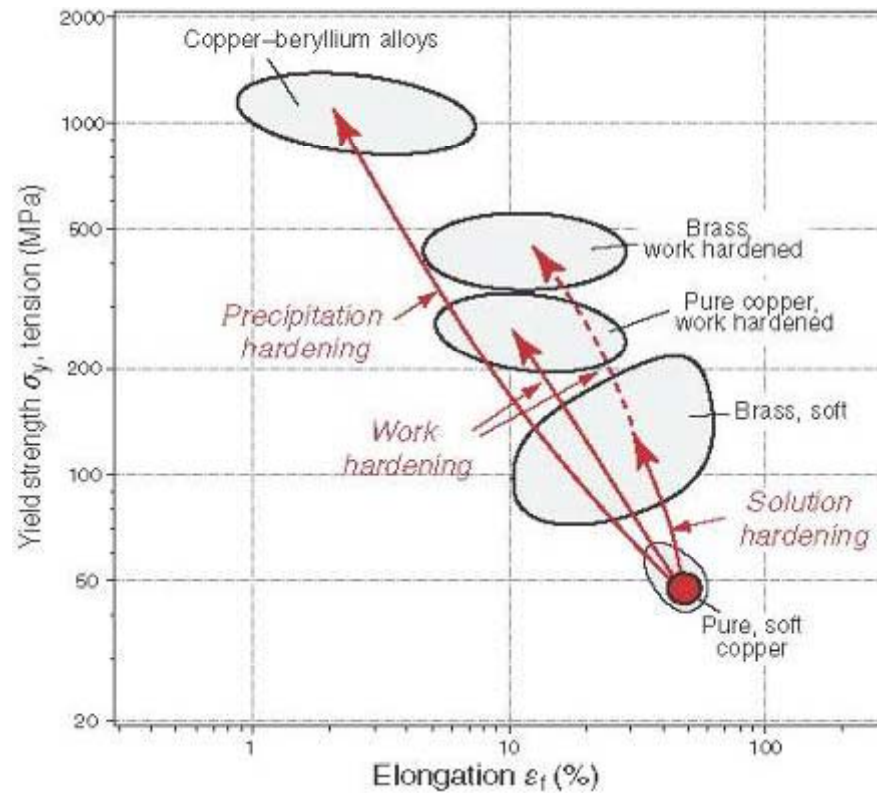
(b) Mechanical working



(c) Precipitation hardening

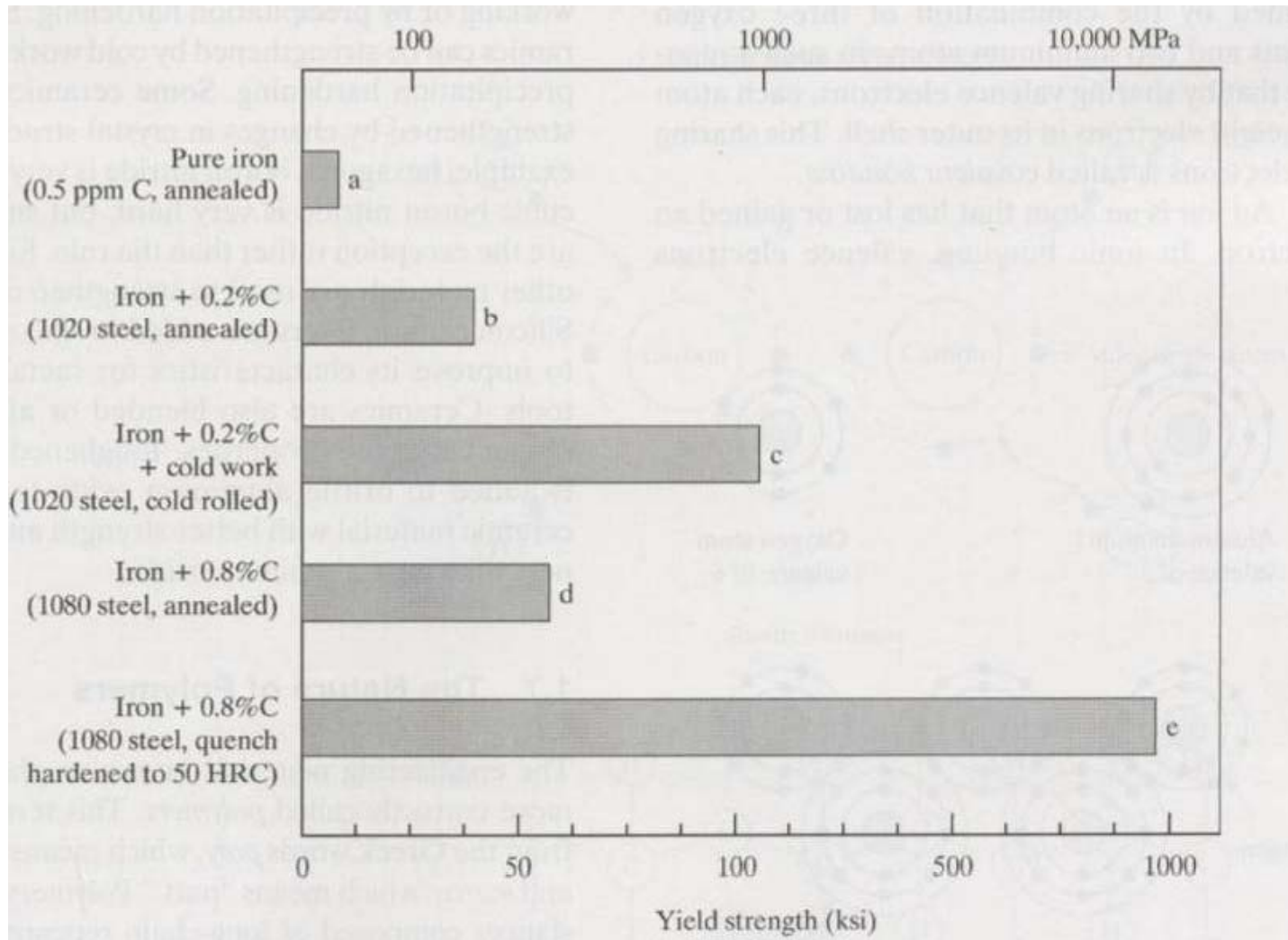


(d) Quench hardening



Strengthening mechanisms and the consequent drop in ductility, here shown for copper alloys.

The mechanisms are frequently combined. The greater the strength,
the lower the ductility (the elongation to fracture, ϵ_f).



Watch 6 min tape!

Now the Fun Stuff:

- HEAT TREATMENT OF STEELS:

Steel Crystal Structures:

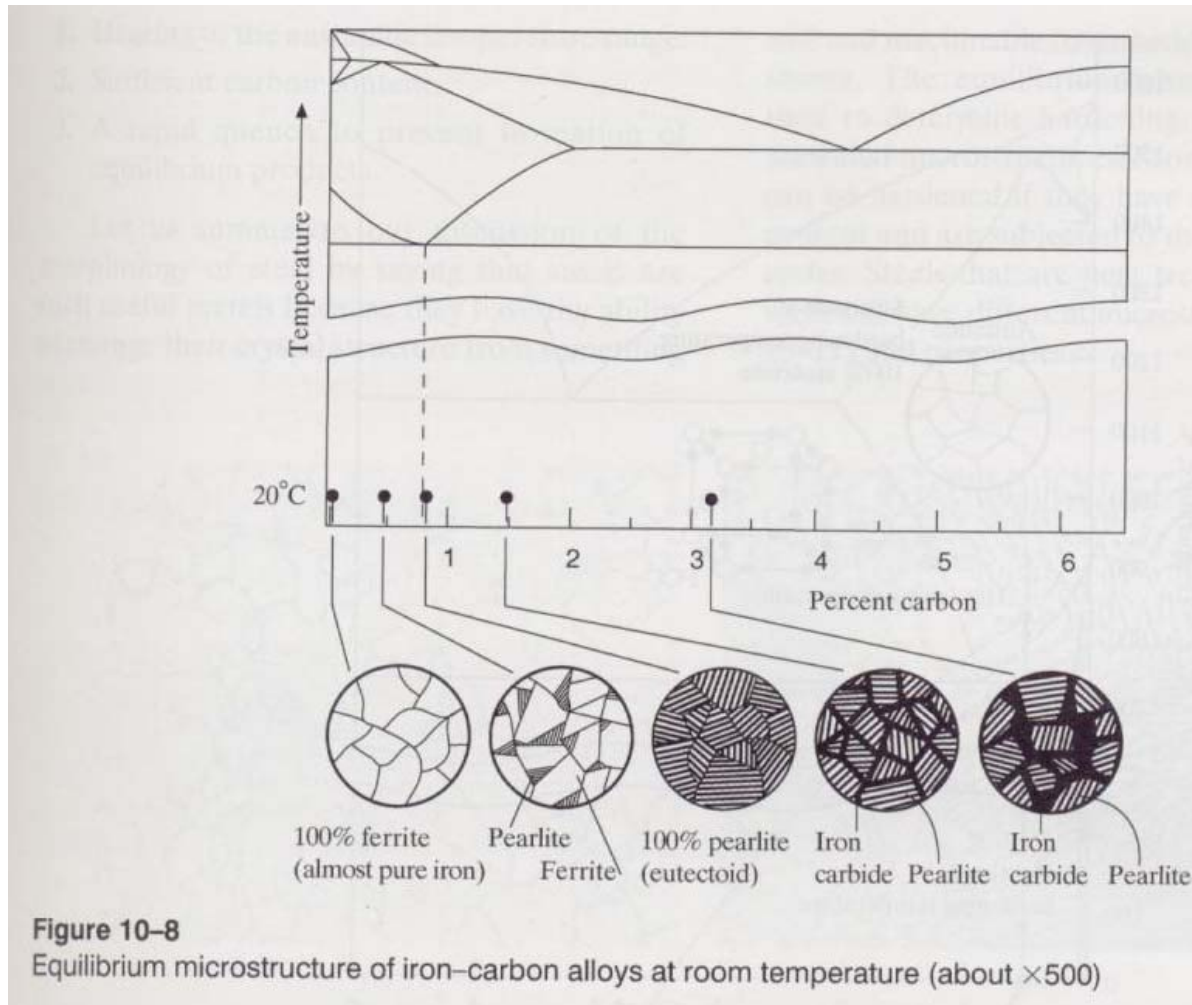
- Ferrite – BCC iron w/ carbon in solid solution (soft, ductile, magnetic)

- Austenite – FCC iron with carbon in solid solution (soft, moderate strength, non-magnetic)

- Cementite – Compound of carbon and iron Fe_3C (Hard and brittle)

- Pearlite – alternate layers of ferrite and cementite.

- Martensite – iron – carbon w/ body centered tetragonal – result of heat treat and quench



HT: ferrite then austenite then martensite



(a)



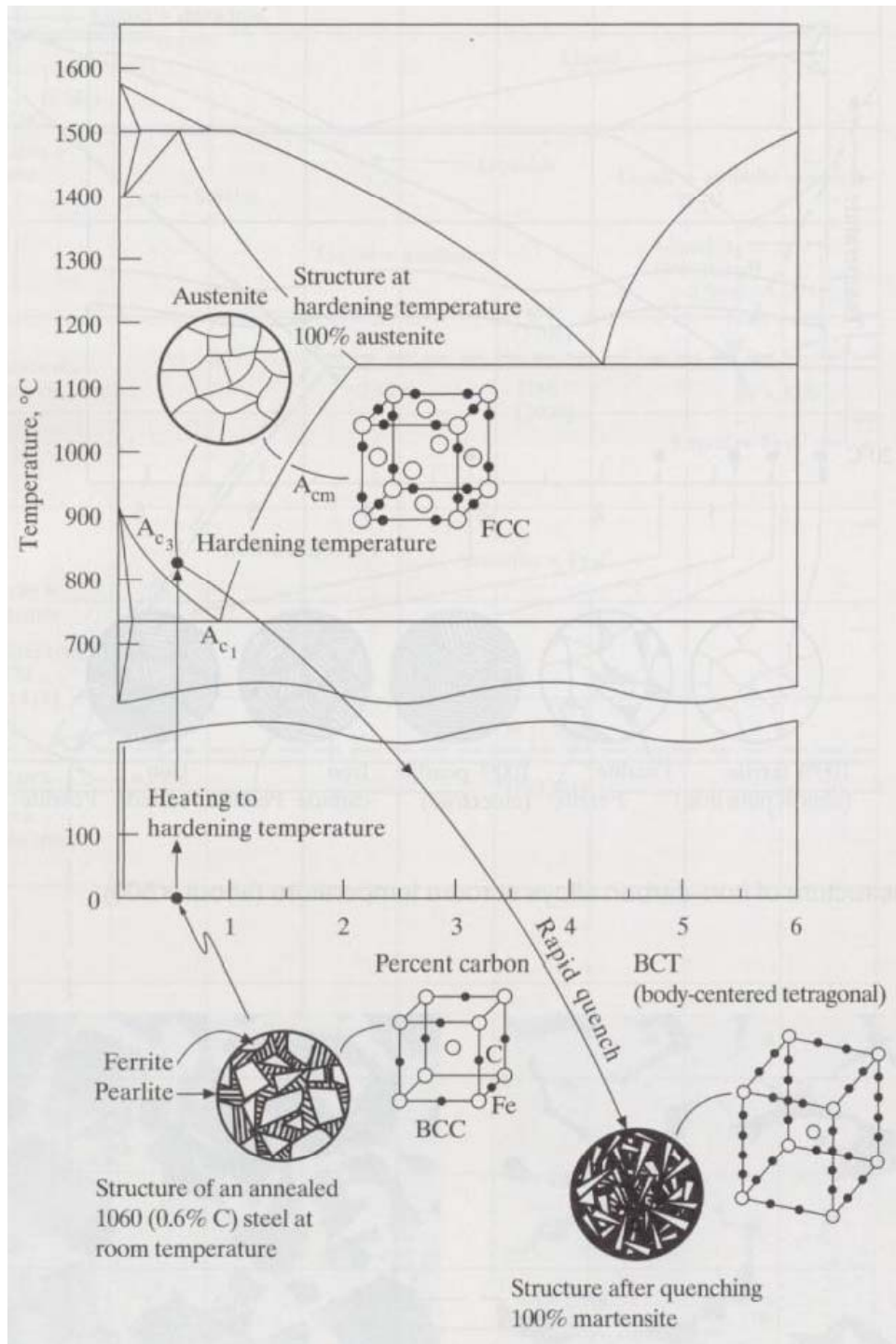
(b)

Figure 10-9

Microstructures of annealed carbon steel. (a) About 0.2% C. (b) About 0.6% C. The light areas are ferrite and the dark are pearlite ($\times 400$).

Heat Treatment of Steels

- Steel = 0.06% to 1.0% carbon
- Must have a carbon content of at least .6% (ideally) to heat treat.
- Must heat to austenitic temperature range.
- Must rapid quench to prevent formation of equilibrium products.
- Basically crystal structure changes from BCC to FCC at high Temp.
- The FCC can hold more carbon in solution and on rapid cooling the crystal structure wants to return to its BCC structure. It cannot due to trapped carbon atoms. The net result is a distorted crystal structure called body centered tetragonal called *martensite*.



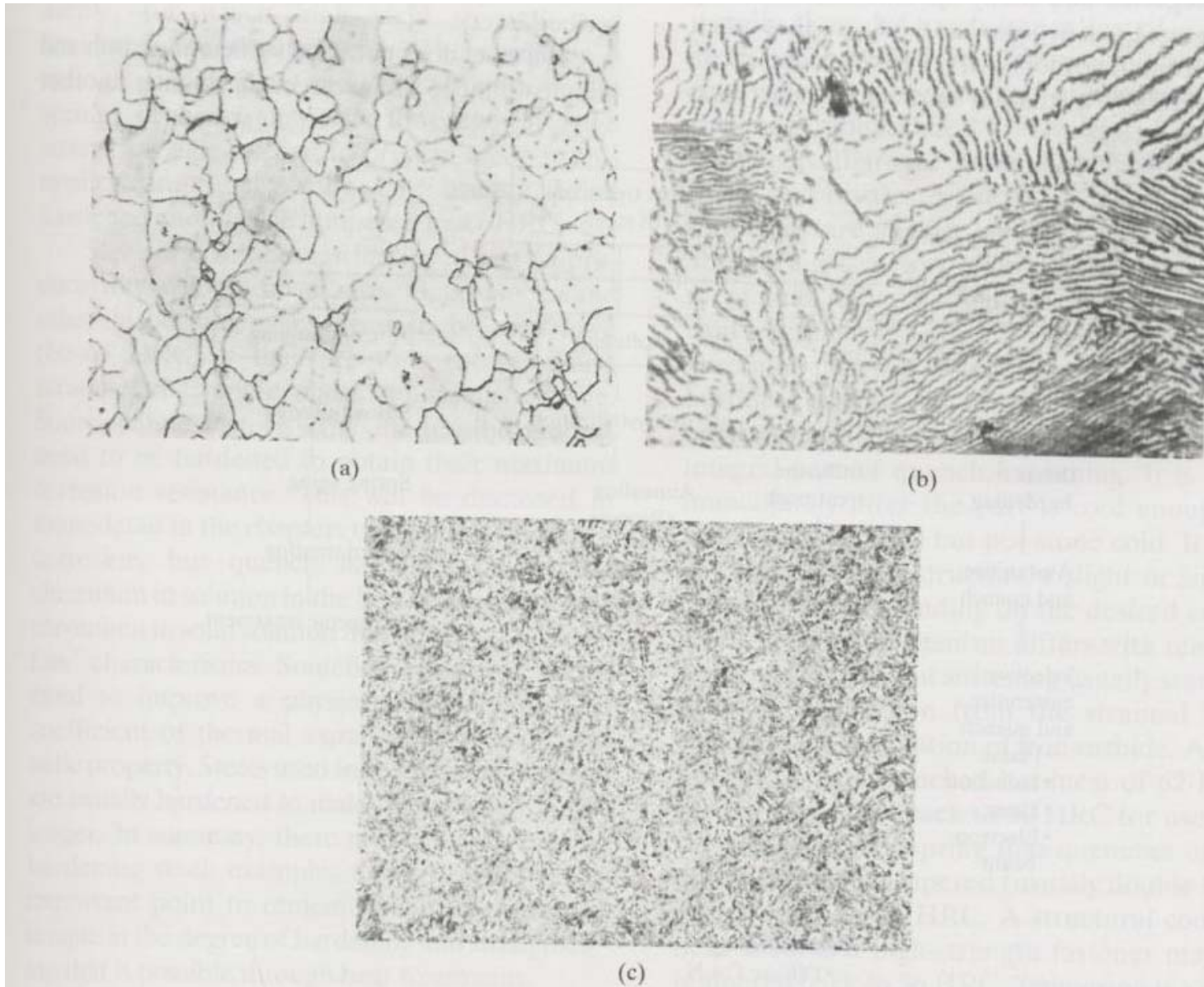
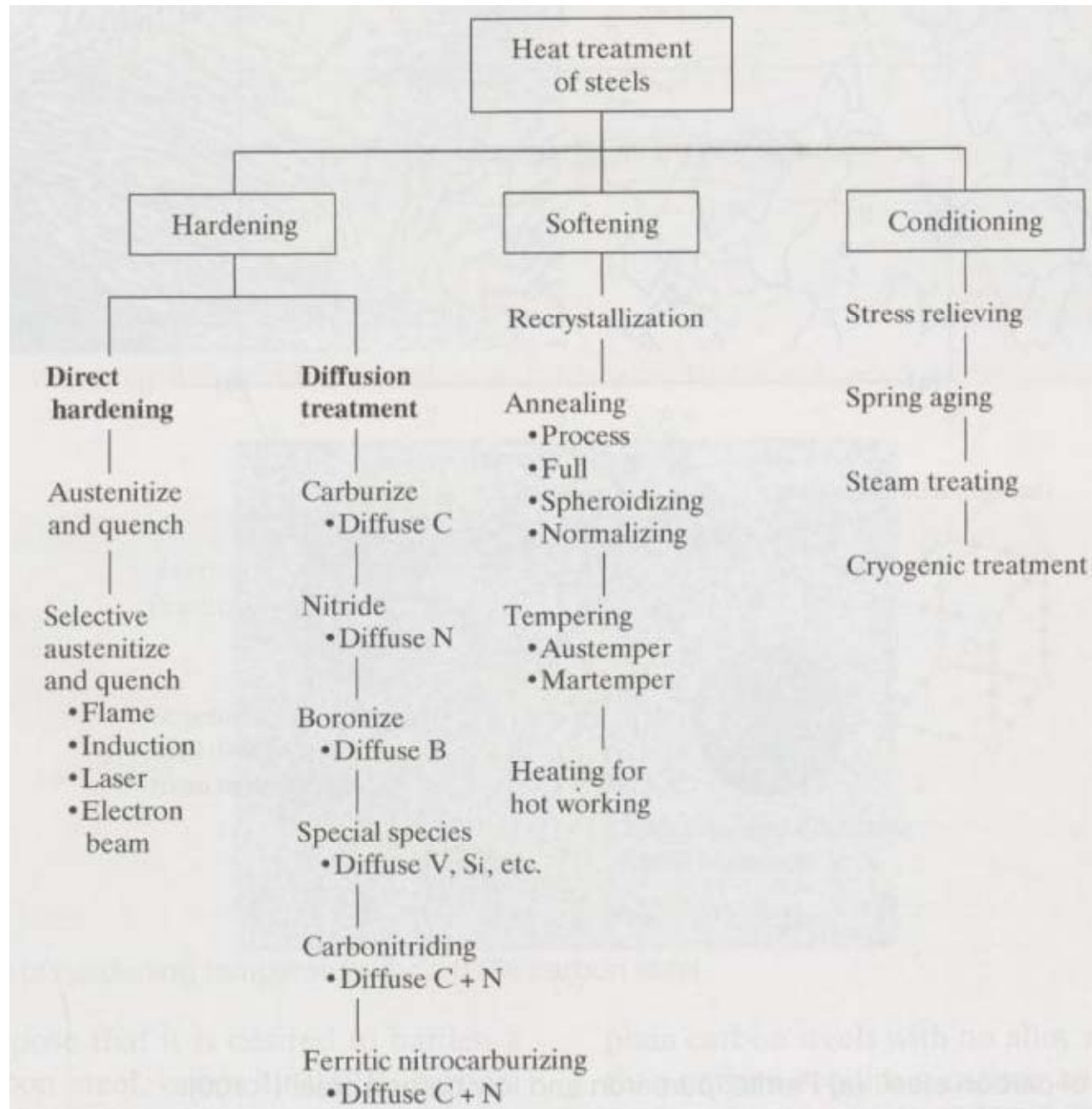


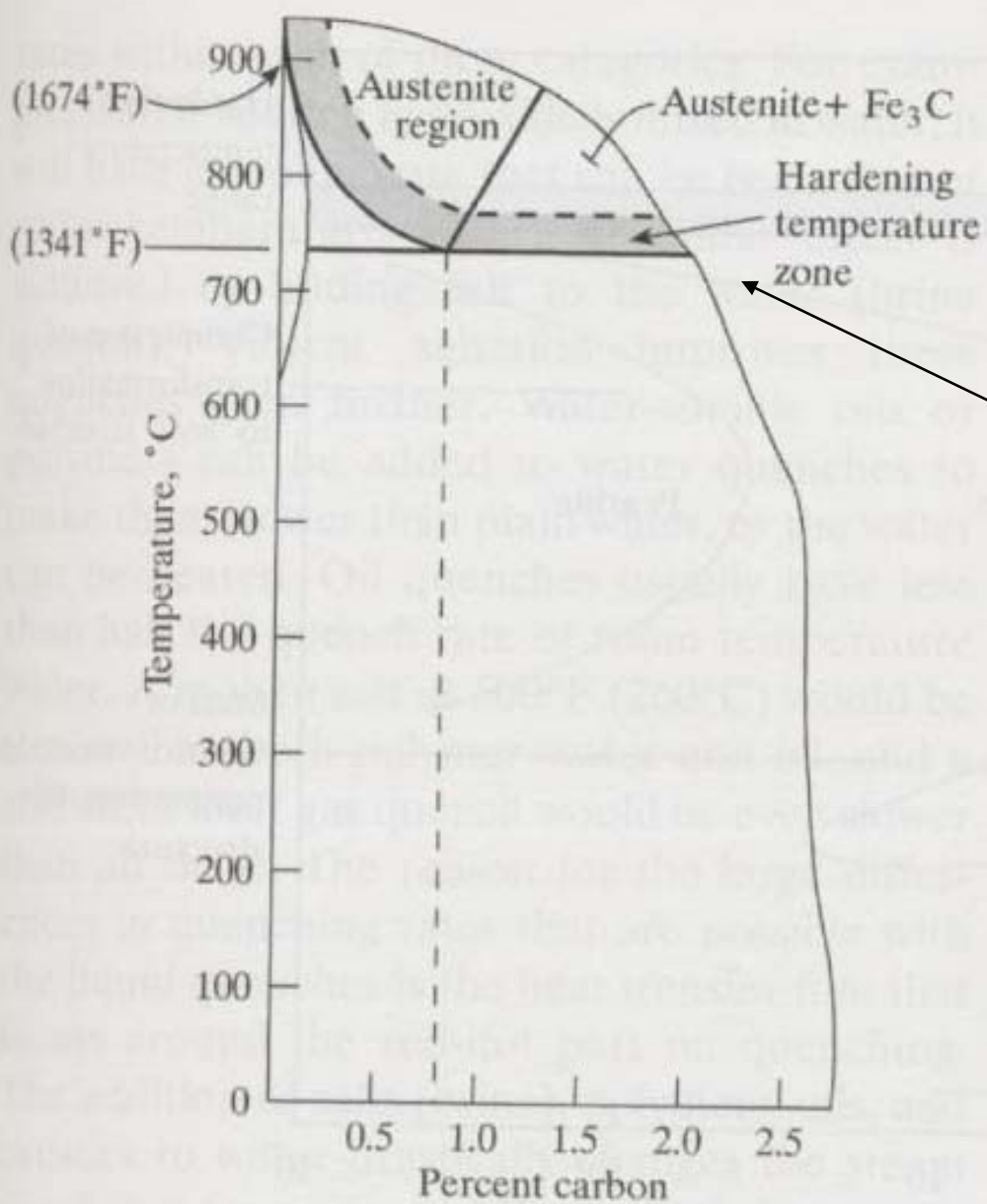
Figure 10-11

Microstructures of carbon steel. (a) Ferrite: pure iron and low-carbon steel ($\times 100$). Austenite has about the same microscopic appearance. (b) Pearlite: an annealed 0.8% C steel is 100% pearlite. The dark lines are Fe_3C ; the light areas are ferrite ($\times 1330$). (c) Martensite: quench-hardened steels ($\times 500$).



10.4 Direct Hardening – *Austenitizing and quench:*

- Austenitizing – again taking a steel with .6% carbon or greater and heating to the austenite region.
- Rapid quench to trap the carbon in the crystal structure – called martensite (BCT)
- Quench requirements determined from isothermal transformation diagram (IT diagram).
- Get “Through” Hardness!!!



Austenitizing:

Heat to austenite range.
 Want to be close to
 transformation
 temperature to get fine
 grain structure.

Figure 10-14
 Hardening temperature range shown on the
 iron-carbon diagram

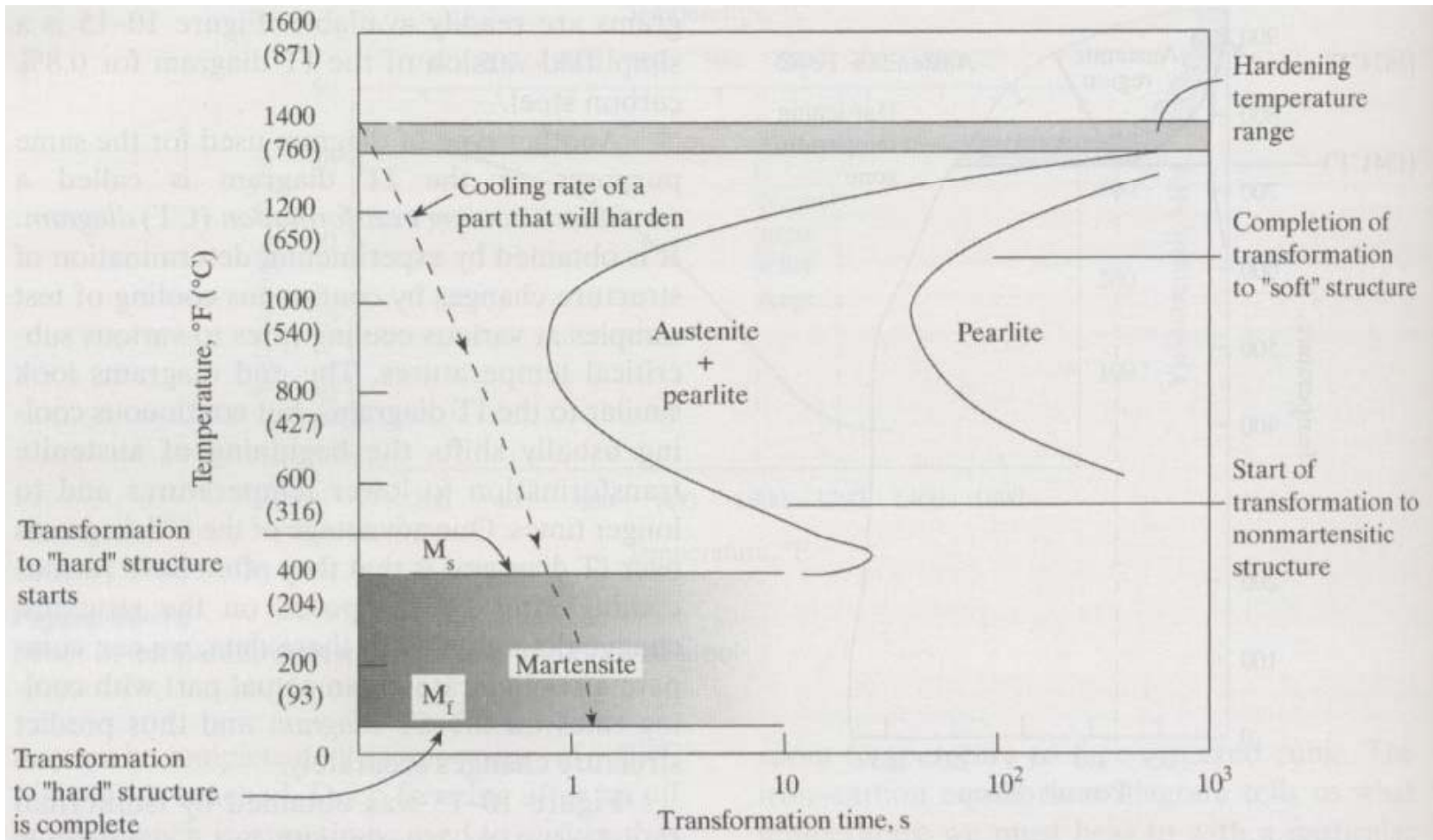


Figure 10-15
Typical time-temperature transformation diagram (TTT)

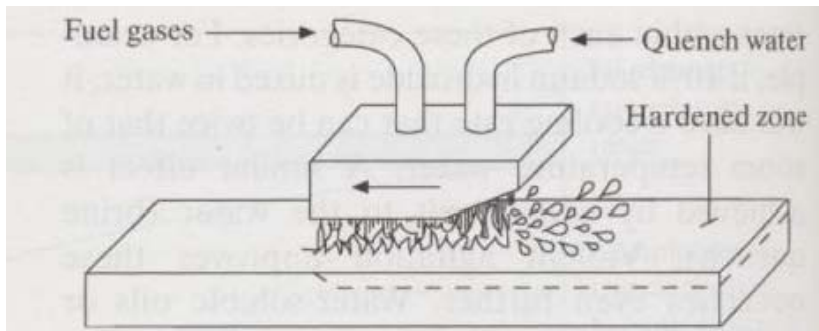
For this particular steel want to cool from about 1400 F to <400 F in about 1 second!

Quenching:

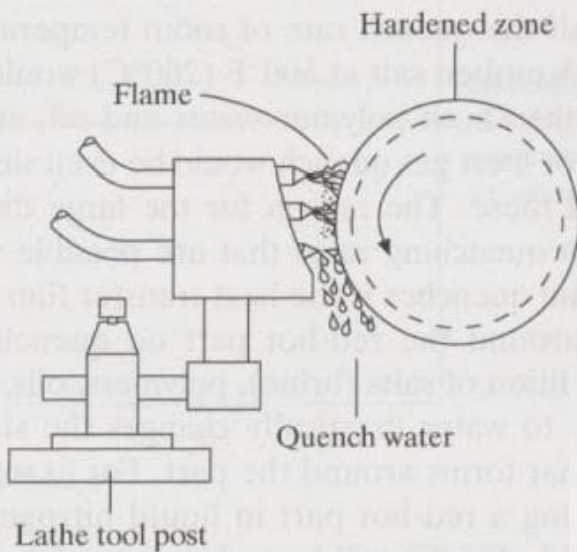
- Depending on how fast steel must be quenched (from IT diagram), the heat treater will determine type of quenching required:
 - Water (most severe)
 - Oil
 - Molten Salt
 - Gas/ Air (least severe)
 - Many phases in between!!! Ex: add water/polymer to water reduces quench time! Adding 10% sodium hydroxide or salt will have twice the cooling rate!

10.4 Direct Hardening - *Selective Hardening* :

- Same requirements as austenitizing:
 - Must have sufficient carbon levels ($>0.4\%$)
 - Heat to austenite region and quench
- Why do?
 - When only desire a select region to be hardened: Knives, gears, etc.
 - Object too big to heat in furnace! Large casting w/ wear surface
- Types:
 - Flame hardening, induction hardening, laser beam hardening



Flame hardening of flat plates



Flame hardening round bars in a lathe

Figure 10-16
Typical flame-hardening systems

Flame Hardening:

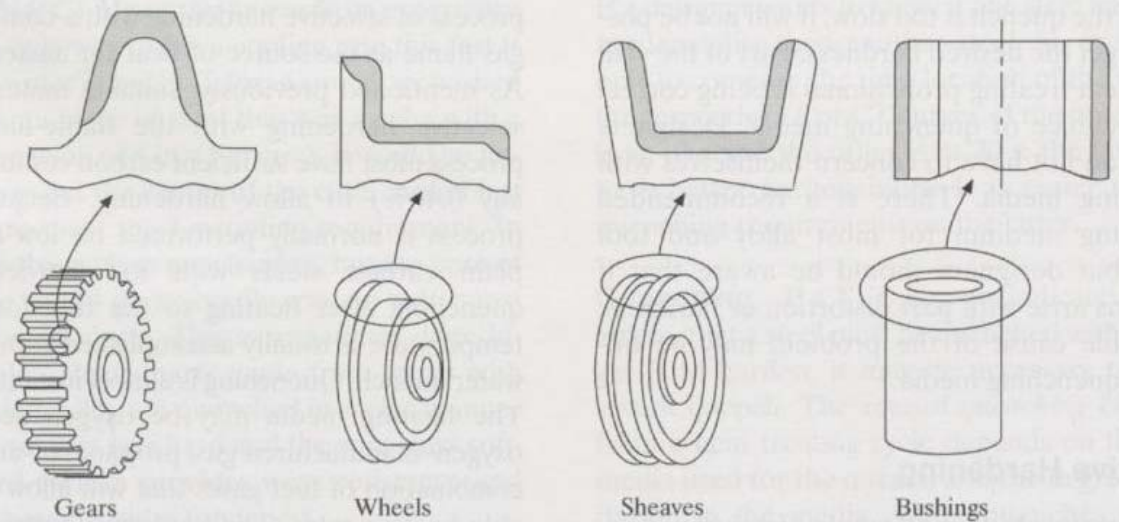
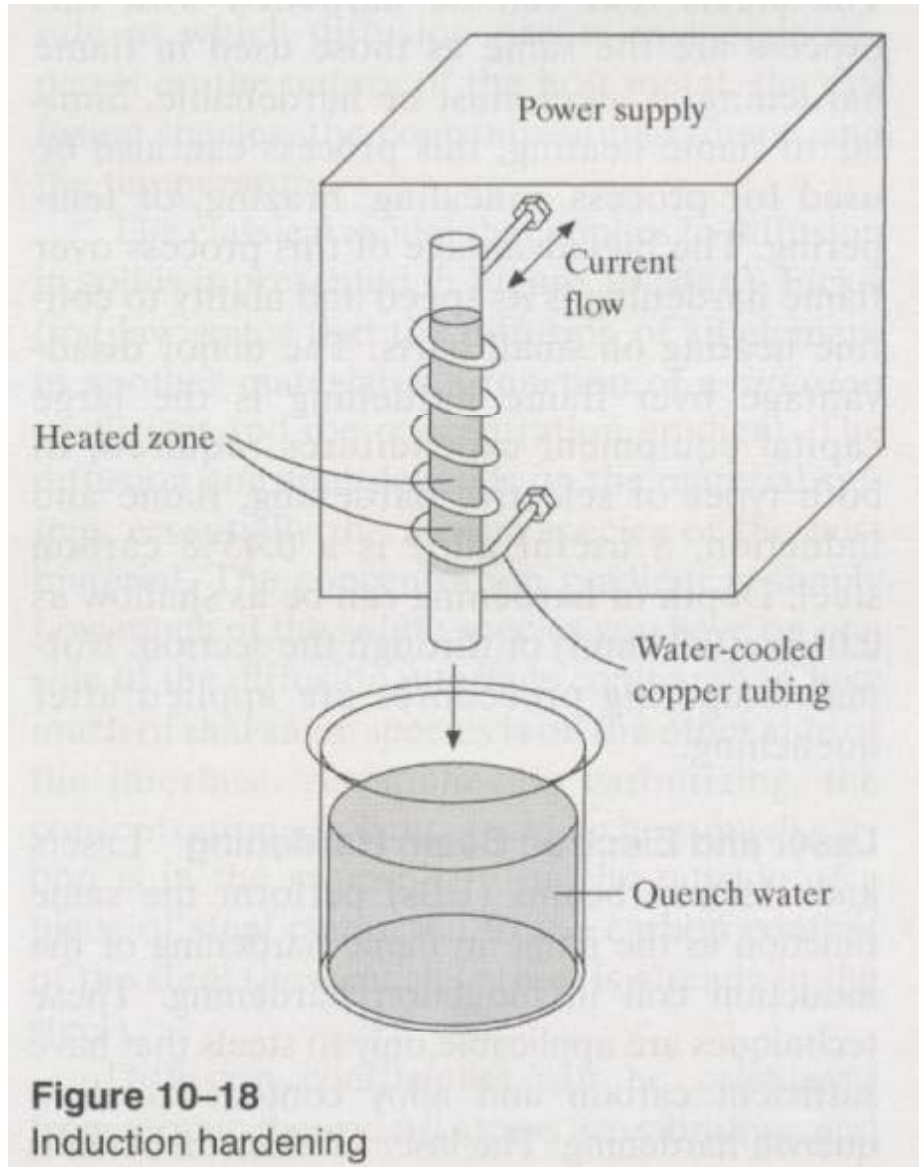


Figure 10-17
Flame-hardening profiles (white areas) for typical mechanical components

Induction Hardening



Diffusion Hardening (aka Case Hardening):

- Why do?
 - Carbon content too low to through harden with previous processes.
 - Desire hardness only in select area
 - More controlled versus flame hardening and induction hardening.
 - Can get VERY hard local areas (i.e. HRC of 60 or greater)
 - Interstitial diffusion when tiny solute atoms diffuse into spaces of host atoms
 - Substitutional diffusion when diffusion atoms too big to occupy interstitial sites – then must occupy vacancies

Figure 10-20

Basic concepts for diffusion processes

Diffusion concepts

(a) Model

$$\text{Fick's law: } J = D \frac{dc}{dx}$$

where J = flux of atoms (atoms/time/area)

D = diffusion coefficient (area/time)

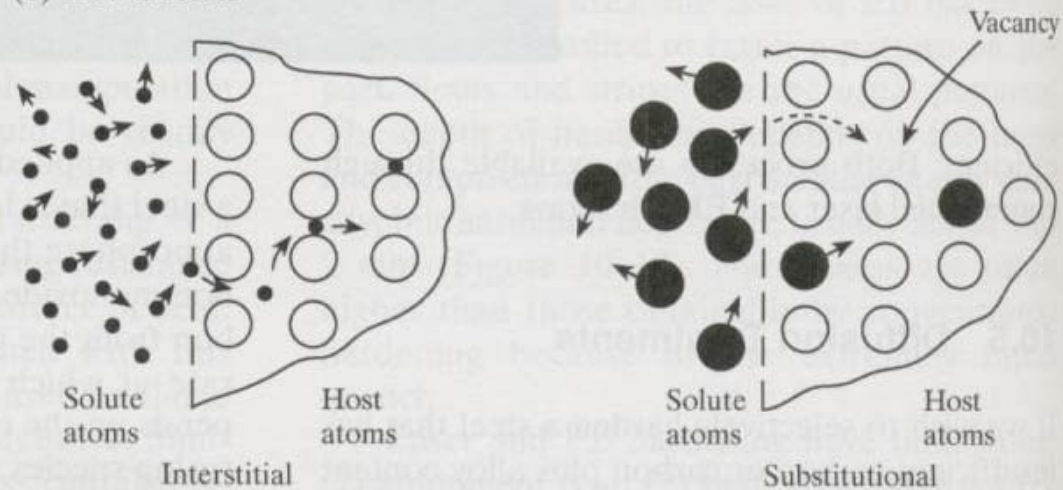
$\frac{dc}{dx}$ = concentration gradient (c = atoms/volume; x = distance)

$$\text{Diffusion coefficient: } D = D_0 e^{\Delta H/RT}$$

D_0 = a diffusion constant for a material

$\Delta H/RT$ = activation energy for process to occur;
 ΔH depends on the material system,
 R is a constant, and T is absolute temperature

(b) How it occurs



(c) Where it applies

	Solute	Host
Carburizing	C	Low-carbon steels
Nitriding	N	Nitriding steels
Carbonitriding	C + N	Low-carbon steels
Boronizing	B	Low-carbon steels
Chromizing	Cr	Low- and high-carbon steels

Diffusion Hardening:

- Requirements:
 - High temp (> 900 F)
 - Host metal must have low concentration of the diffusing species
 - Must be atomic suitability between diffusing species and host metal

Diffusion Hardening:

- Most Common Types:
 - Carburizing
 - Nitriding
 - Carbonitriding
 - Cyaniding

Diffusion Hardening - *Carburizing*:

- Pack carburizing most common:
 - Part surrounded by charcoal treated with activating chemical – then heated to austenite temperature.
 - Charcoal forms CO₂ gas which reacts with excess carbon in charcoal to form CO.
 - CO reacts with low-carbon steel surface to form atomic carbon
 - The atomic carbon diffuses into the surface
 - Must then be quenched to get hardness!

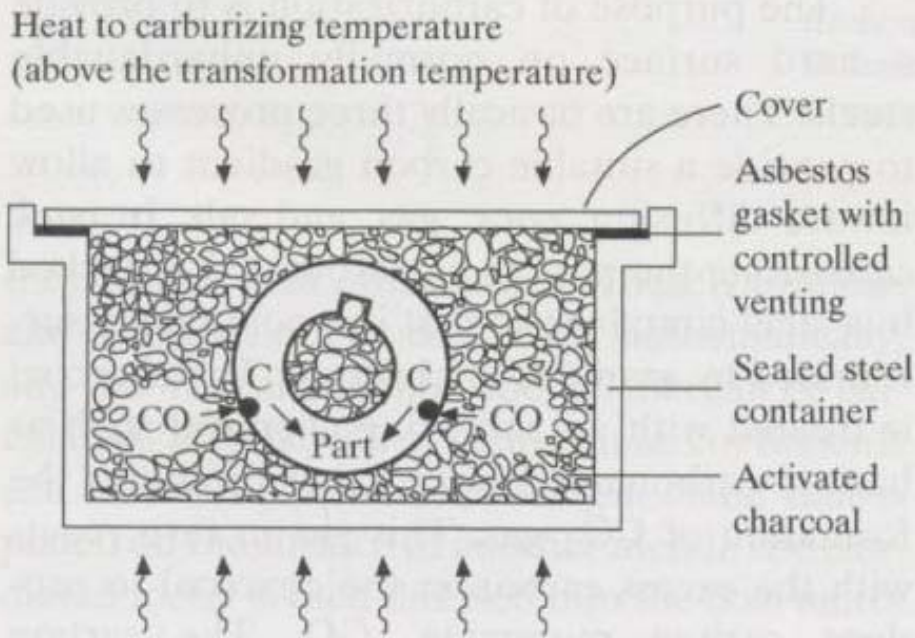


Figure 10-21
Pack carburizing

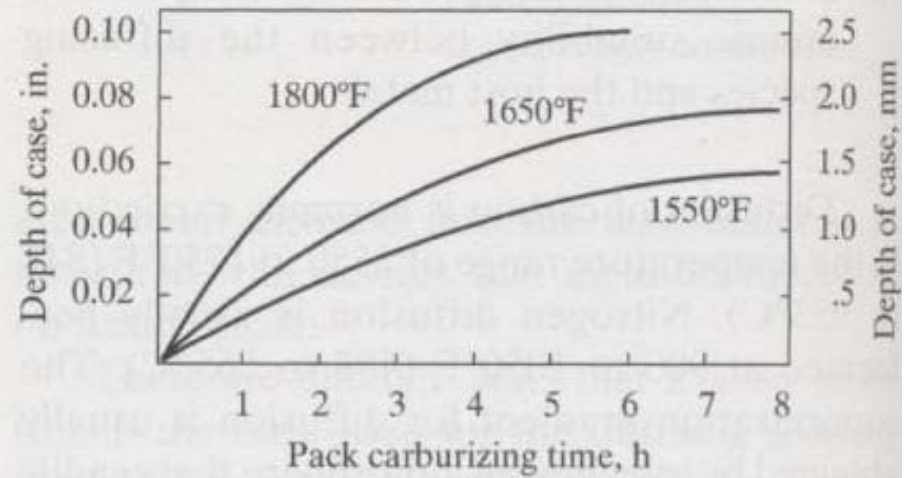
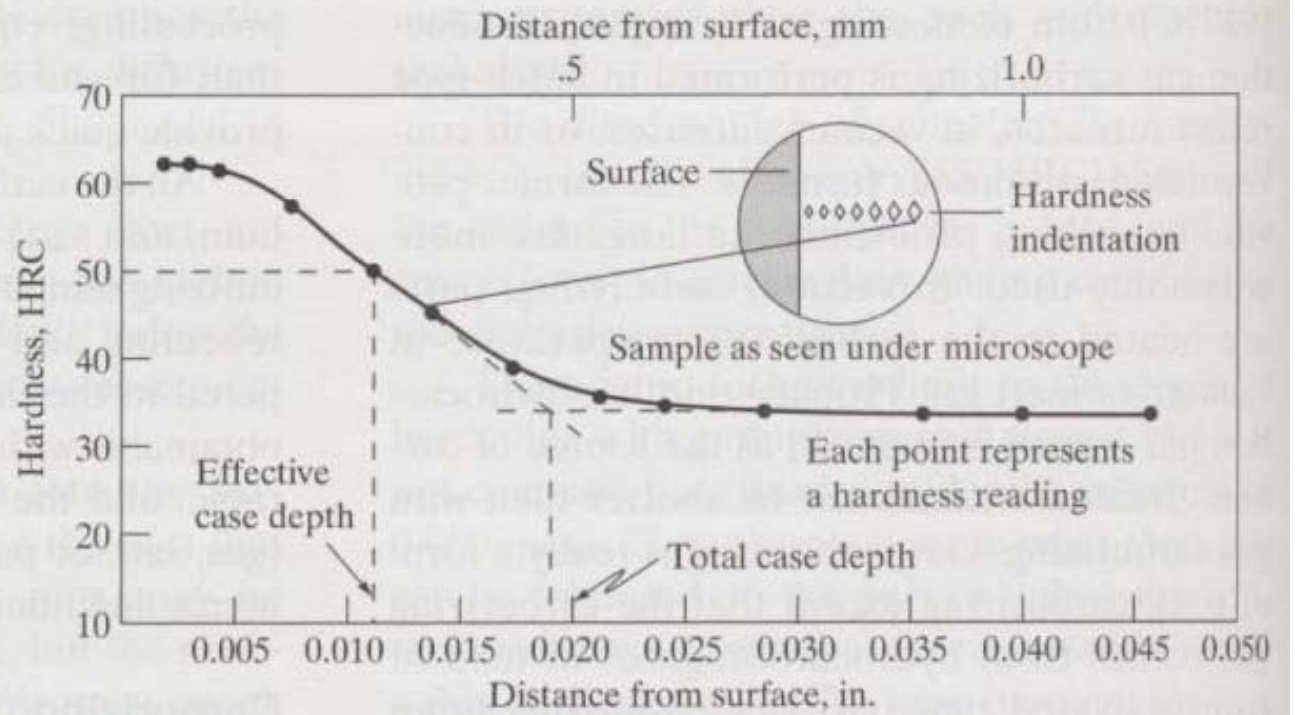


Figure 10-22
Effect of carburizing temperature on case depth
Source: G. M. Enos and W. E. Fontaine. *Elements of Heat Treatment*. New York: John Wiley & Sons, Inc., 1963.

Figure 10-23

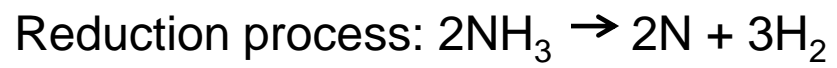
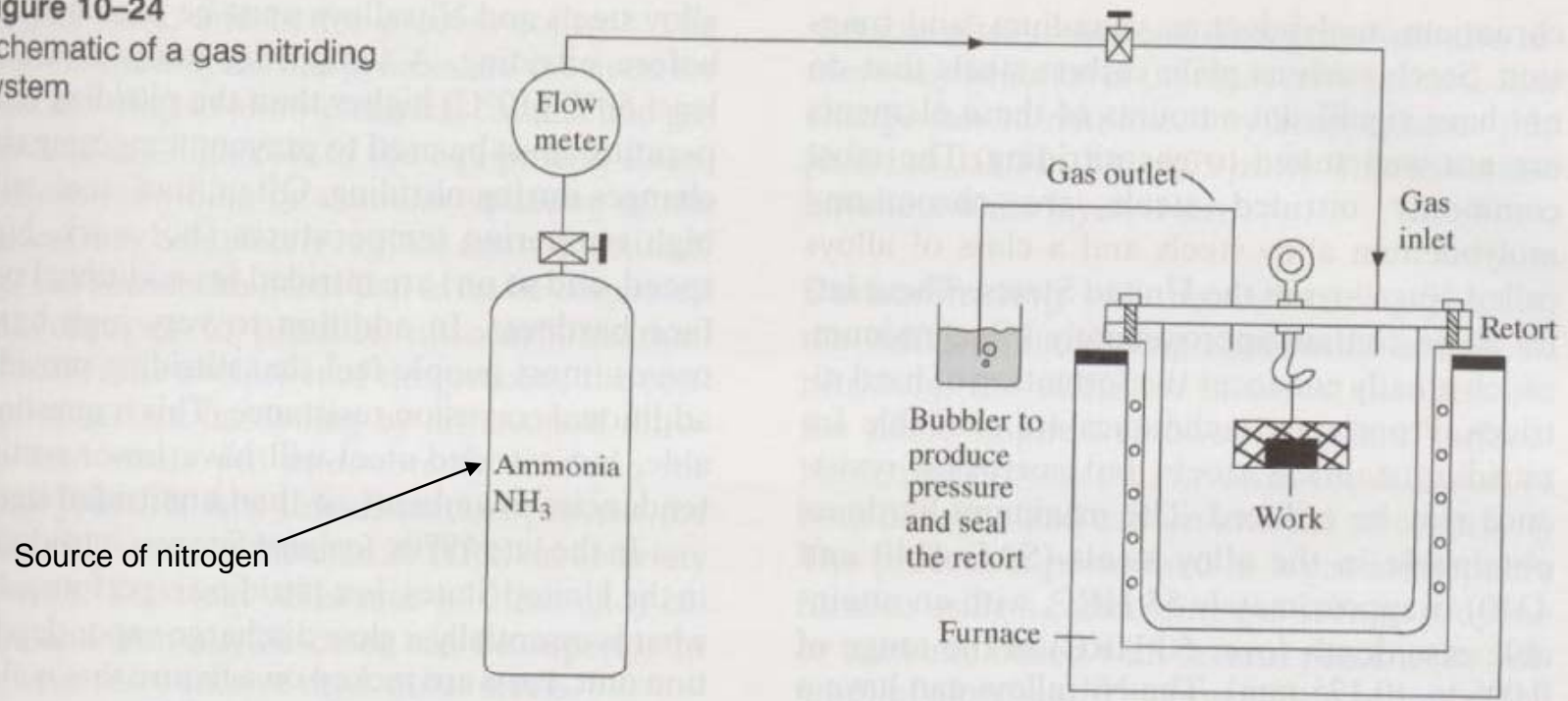
Determination of carburized or carbonitrided case depth by microhardness survey

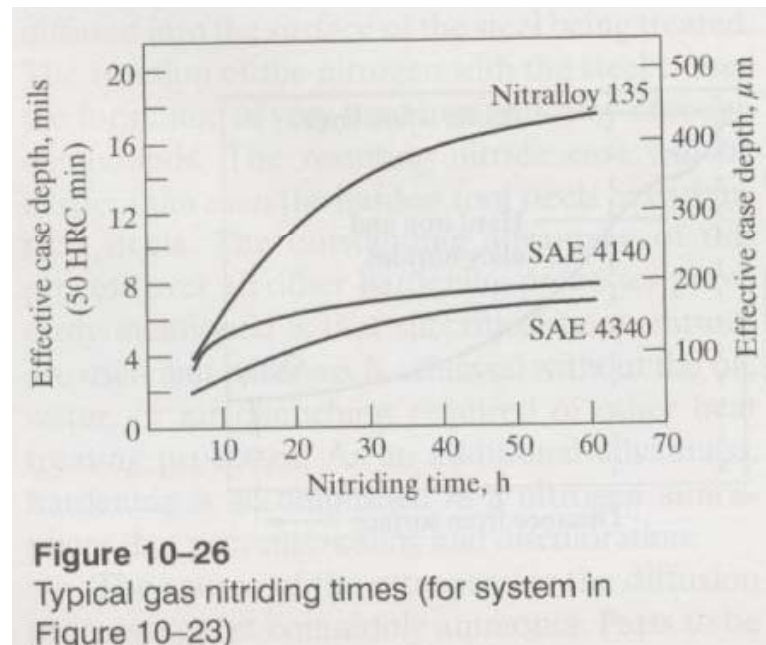
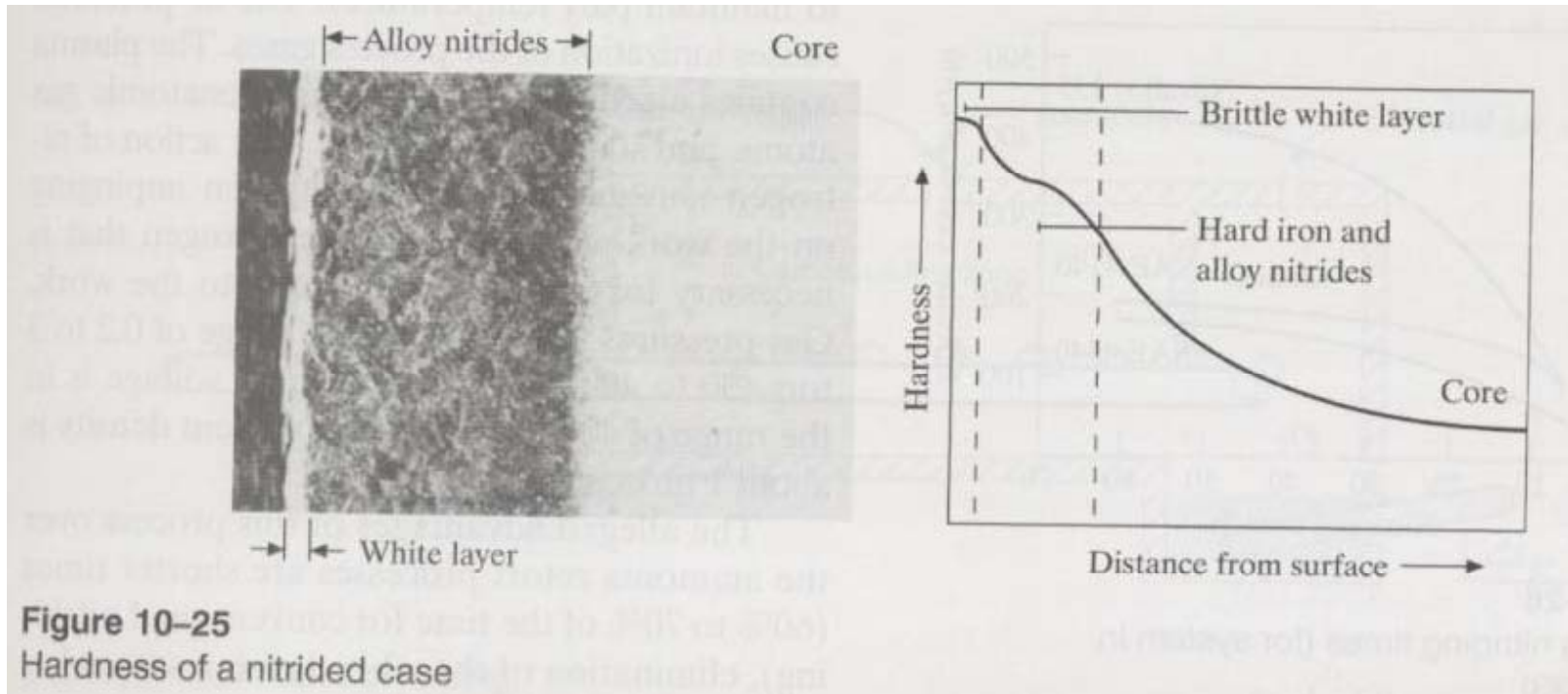


Diffusion Hardening - *Nitriding*:

- Nitrogen diffused into surface being treated. Nitrogen reacts with steel to form very hard iron and alloy nitrogen compounds.
- Process does not require quenching – big advantage.
- The case can include a white layer which can be brittle – disadvantage
- More expensive than carburizing

Figure 10-24
Schematic of a gas nitriding system





10.6 Softening and Conditioning -

- Recrystallization
- Annealing
 - Process anneal
 - Stress relief anneal
 - Normalizing
- Tempering

10.6 Softening and Conditioning - Recrystallization

- Done often with cold working processes
- Limit to how much steel can be cold worked before it becomes too brittle.
- This process heats steel up so grains return to their original size prior to subsequent cold working processes.
- Also done to refine coarse grains

10.6 Softening and Conditioning - *Annealing*

- Annealing – primary purpose is to soften the steel and prepare it for additional processing such as cold forming or machining.
- If already cold worked - allows recrystallization.

10.6 Softening and Conditioning - *Annealing*

- What does it do?
 1. Reduce hardness
 2. Remove residual stress (stress relief)
 3. Improve toughness
 4. Restore ductility
 5. Refine grain size

10.6 Softening and Conditioning - *Annealing*

- Process Steps:
 1. Heat material into the austenite region (i.e. above 1600F) – rule of thumb: hold steel for one hour for each one inch of thickness
 2. Slowly furnace cool the steel – DO NOT QUENCH
 3. Key slow cooling allows the C to precipitate out so resulting structure is coarse pearlite with excess ferrite
 4. After annealing steel is quite soft and ductile

Annealing versus Austenitizing:

- End result: One softens and the other hardens!
- Both involve heating steel to austenite region.
- Only difference is cooling time:
 - If fast (quenched) C is locked into the structure = *martensite (BCT) = HARD*
 - If slow C precipitates out leading to coarse pearlite (with excess cementite or ferrite) = SOFT

10.6 Softening and Conditioning – Other forms of *Annealing*

- Normalizing – use when max softness not required and cost savings desired (faster than anneal). Air cooled vs. furnace cooled.
- Process Anneal – not heated as high as full anneal.
- Stress Relief Anneal – lower temp (1,000F), slow cooled. Large castings, weldments

10.6 Softening and Conditioning - *Temper*

- Almost always done following heat treat as part of the austenitizing process!
- Because of lack of adequate toughness and ductility after heat treat, high carbon martensite is not a useful material despite its great strength (too brittle).
- Tempering imparts a desired amount of toughness and ductility (at the expense of strength)

10.6 Softening and Conditioning - *Temper*

- Typical HT steps:
 - Austenize: Heat into stable single phase region and HOLD for uniform chemistry single phase austenite.
 - Quench: Rapid cool – crystal changes from Austenite FCC to Martensite BCT which is hard but brittle.
 - Temper: A controlled reheat (BELOW AUSTENITE REGION). The material moves toward the formation of a stable two phase structure – tougher but weaker.
 - Quench: The properties are then frozen in by dropping temperature to stop further diffusion

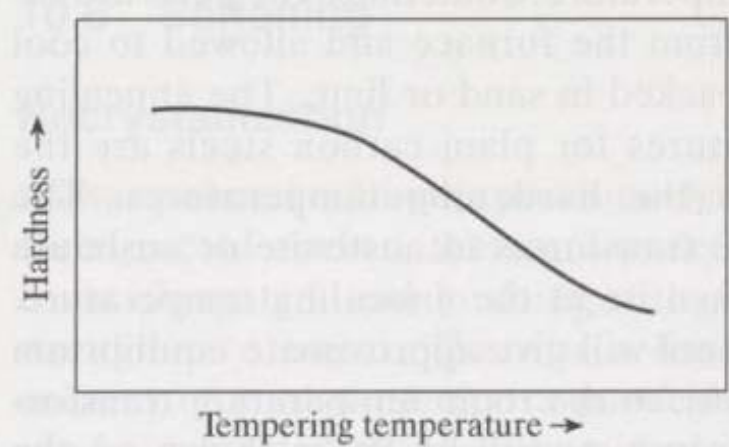
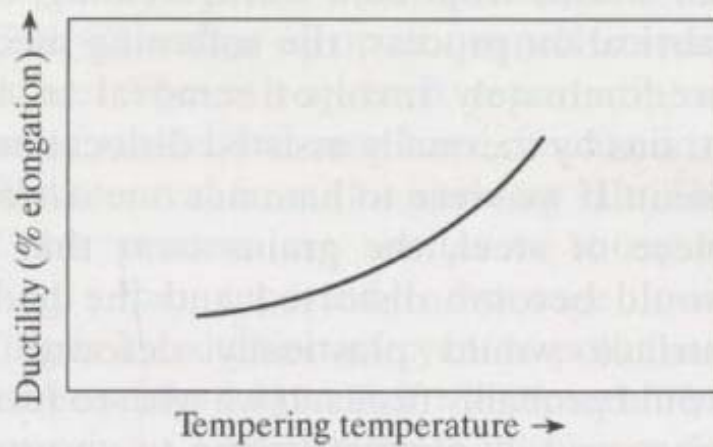
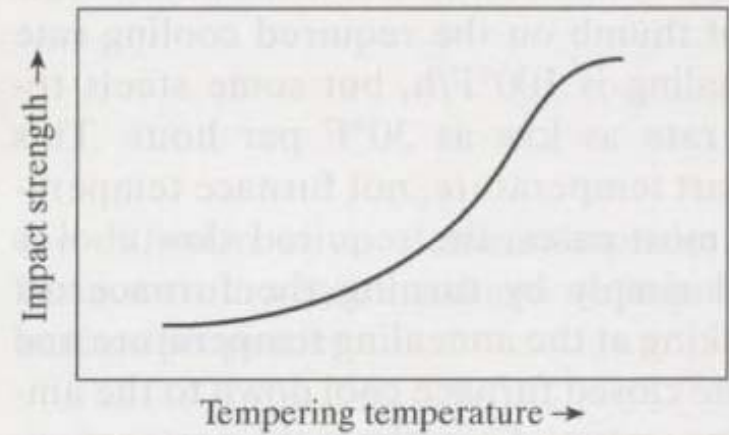
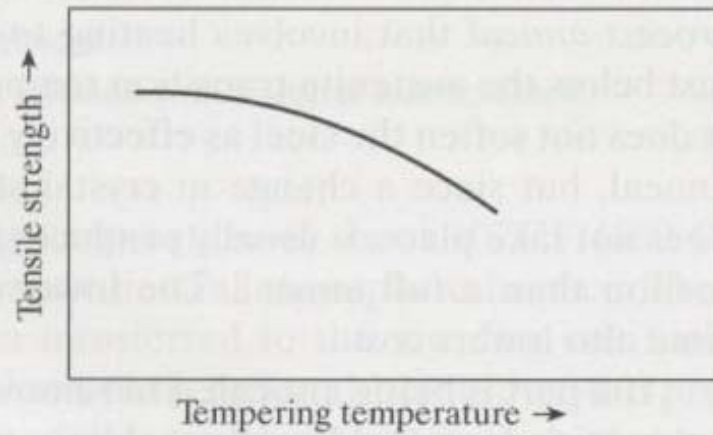


Figure 10-30

Effect of tempering on the properties of a quench-hardened carbon steel (1040–1060)

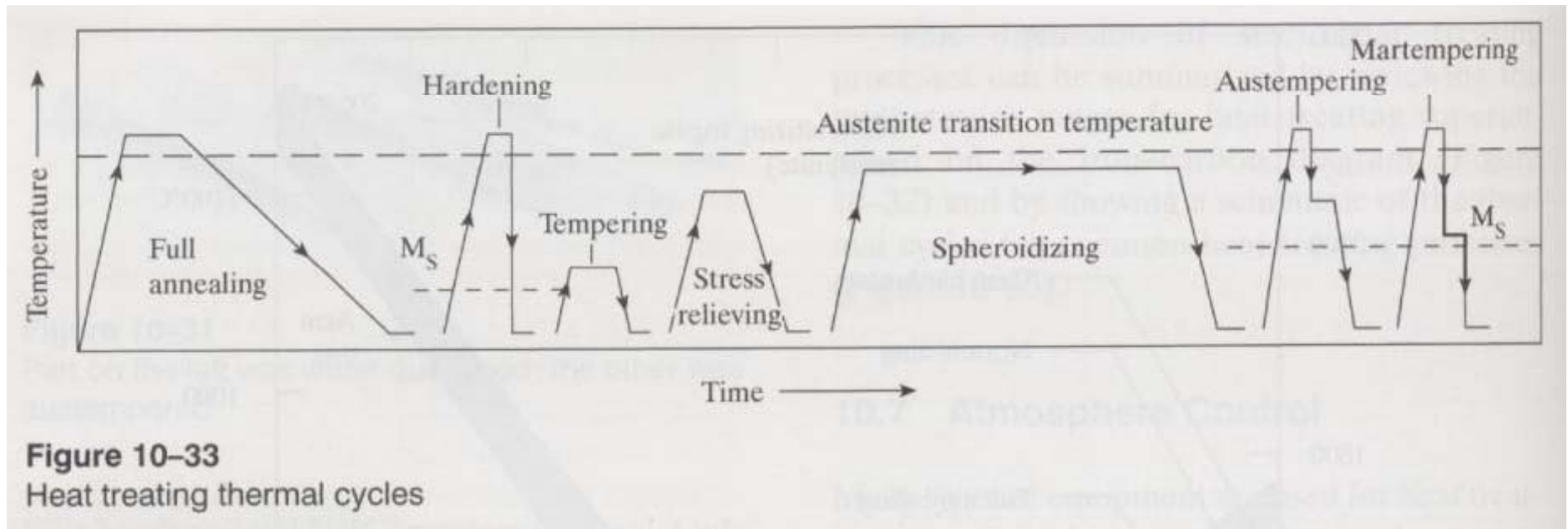


Figure 10-33
Heat treating thermal cycles

The Heat Treat Processes