Phase Transformations in Steel

Course: Phase Transformations
Level: 3rd Stage | Semester: 5
Department of Materials Engineering
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Learning Objectives

By the end of this lecture, students will be able to:

- Understand the main phase transformations in steels using the Fe–Fe_3C phase diagram.
- Identify and differentiate between eutectoid, eutectic, and peritectic reactions.
- Describe how microstructures such as pearlite, bainite, and martensite form during cooling.
- Interpret TTT (Time-Temperature-Transformation) and CCT (Continuous Cooling Transformation) diagrams.
- Relate cooling rate to the final microstructure and resulting mechanical properties of steel.

Eutectoid Transformation in Steel

- In steel (Fe–Fe_3C system), austenite (γ phase) transforms into ferrite (α) and cementite (Fe_3C) at **727°C** — this is called the **eutectoid reaction**.
- However, for the transformation to start in reality, the steel must be **undercool**ed — cooled to a temperature **below 727°C**.
- **Undercooling (ΔT)** provides the driving force for nucleation. The more undercooling, the higher the nucleation rate.
- As nucleation increases, new phases (α and Fe_3C) begin to form and **grow**, completing the transformation.

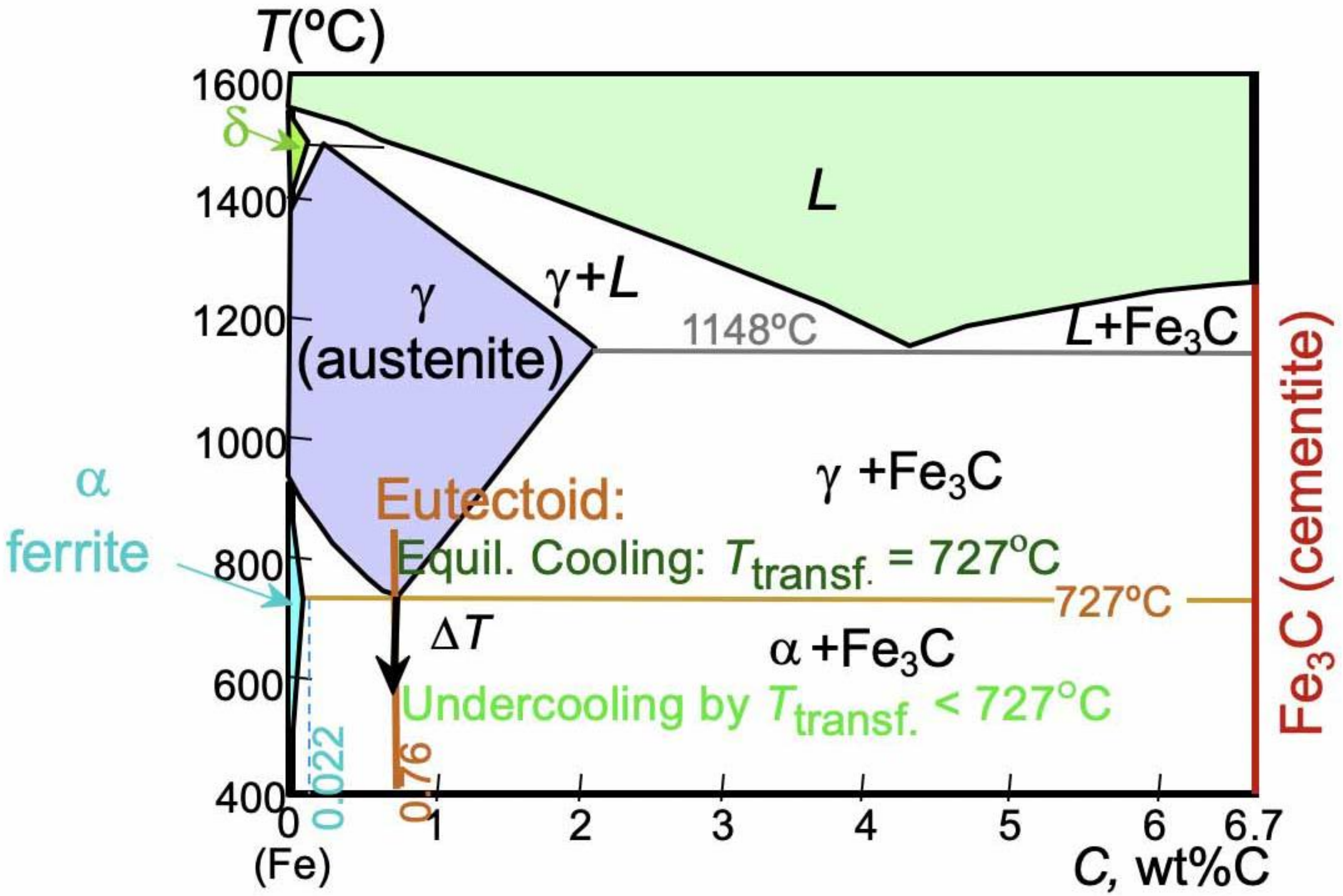
🧊 *Undercooling is essential to start the phase change and control how fast it happens.*

- Eutectoid transf. (Fe-Fe_3C system): $\gamma \Rightarrow \alpha + Fe_3C$
- For transf. to occur, must cool to below 727ºC (i.e., must "undercool")

0.76 wt% C

0.022 wt% C

6.7 wt% C



Invariant Reactions in Fe–Fe_3C Phase Diagram

There are **three important invariant reactions** in the Fe–Fe_3C system:

◆ Peritectic Reaction

- Occurs at **1495°C**
- Liquid + δ-ferrite → austenite (γ)
- Happens when a solid and liquid phase combine to form a second solid phase

◆ Eutectic Reaction

- Occurs at **1148°C**
- Liquid → austenite (γ) + cementite (Fe_3C)
- Liquid transforms into two solid phases simultaneously

◆ Eutectoid Reaction

- Occurs at **727°C**
- Austenite (γ) → ferrite (α) + cementite (Fe_3C)
- Solid phase transforms into two new solid phases

Peritectic Reaction

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

Eutectic Reaction

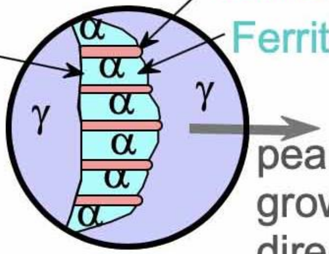
$$\text{Liquid } (4.3\% \text{ C}) \xrightarrow{1148^\circ\text{C}} \gamma \text{ austenite } (2.08\% \text{ C}) + \text{Fe}_3\text{C}\ (6.67\% \text{ C})$$

Eutectoid Reaction

$$\gamma(0.76 \text{ wt\% C}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(0.022 \text{ wt\% C}) + \text{Fe}_3\text{C}\ (6.7 \text{ wt\% C})$$

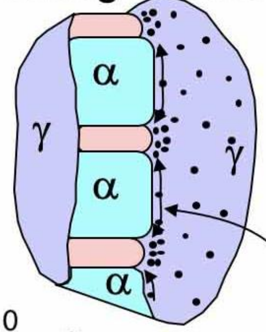
The Fe-Fe_3C Eutectoid Transformation

- Transformation of austenite to pearlite:

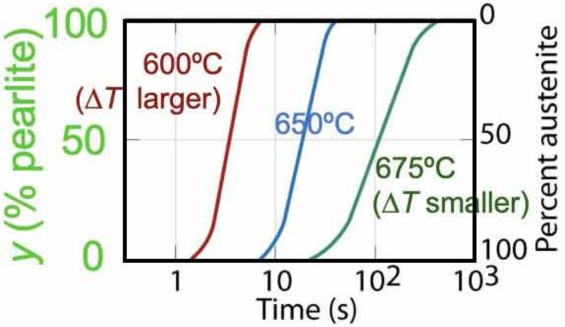


Adapted from Fig. 9.15, *Callister & Rethwisch 8e.*

Diffusion of C during transformation



- For this transformation, rate increases with $[T_{eutectoid} - T]$ (i.e., ΔT).

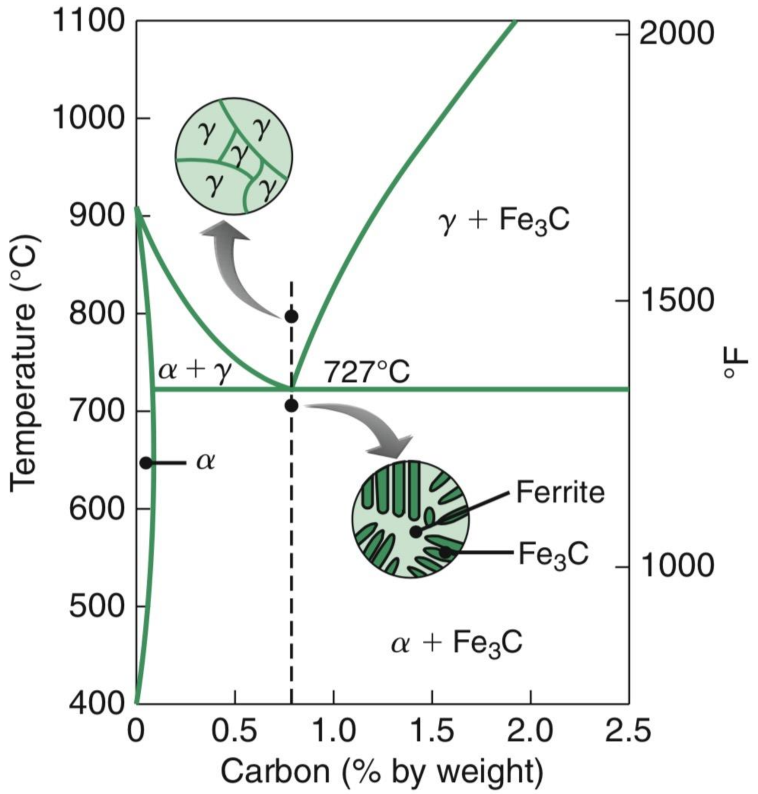


Coarse pearlite → formed at higher temperatures – relatively soft

Fine pearlite → formed at lower temperatures – relatively hard

Pearlite - A two-phase lamellar microconstituent, containing ferrite and cementite, that forms in steels cooled in a normal fashion or isothermally transformed at relatively high temperatures.

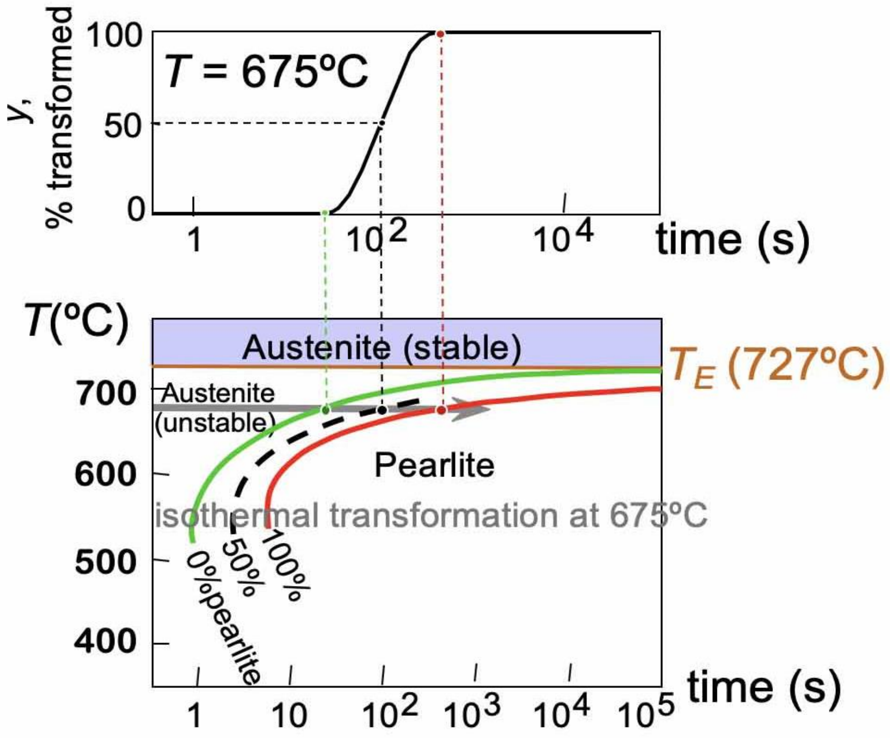
Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.



Generation of Isothermal Transformation Diagrams

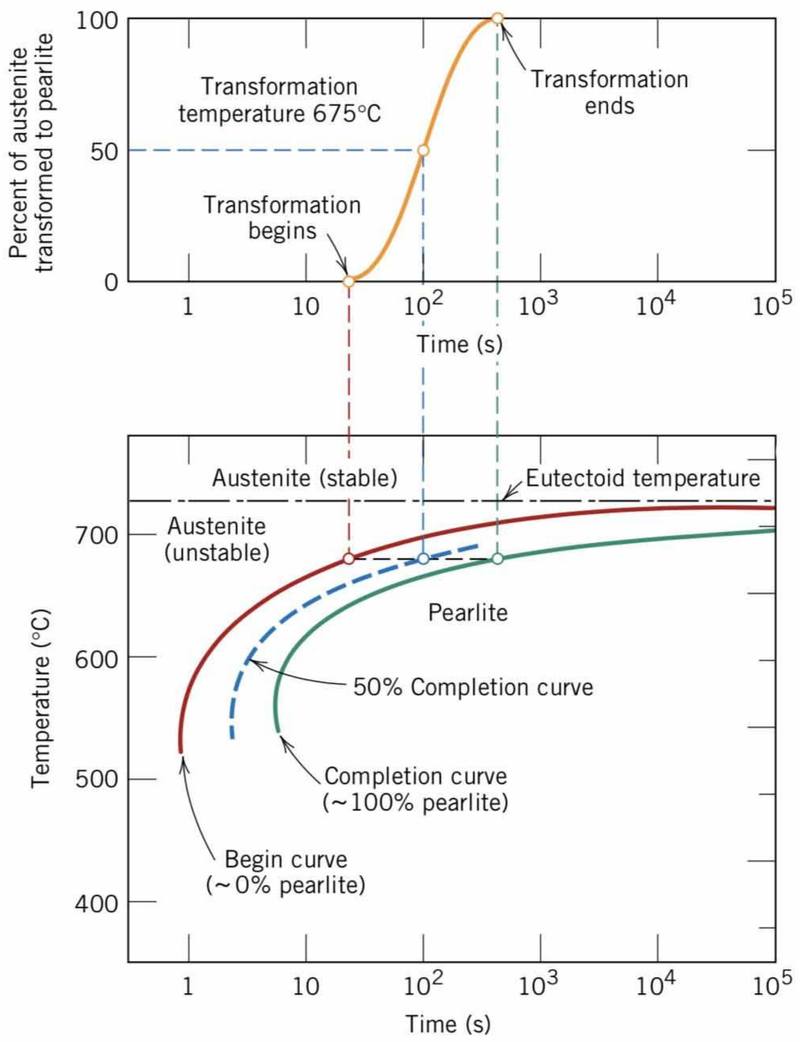
Consider:

- The Fe-Fe_3C system, for $C_0 = 0.76$ wt% C
- A transformation temperature of 675°C.



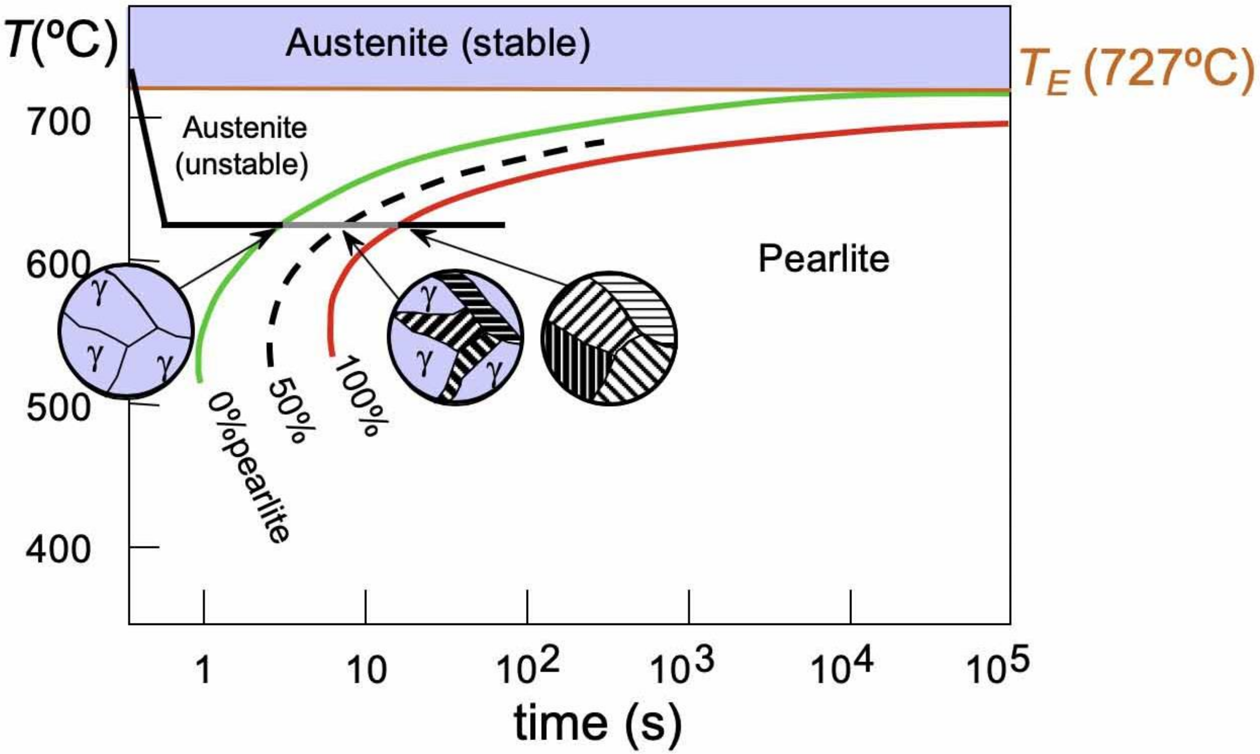
Generation of Isothermal Transformation Diagrams

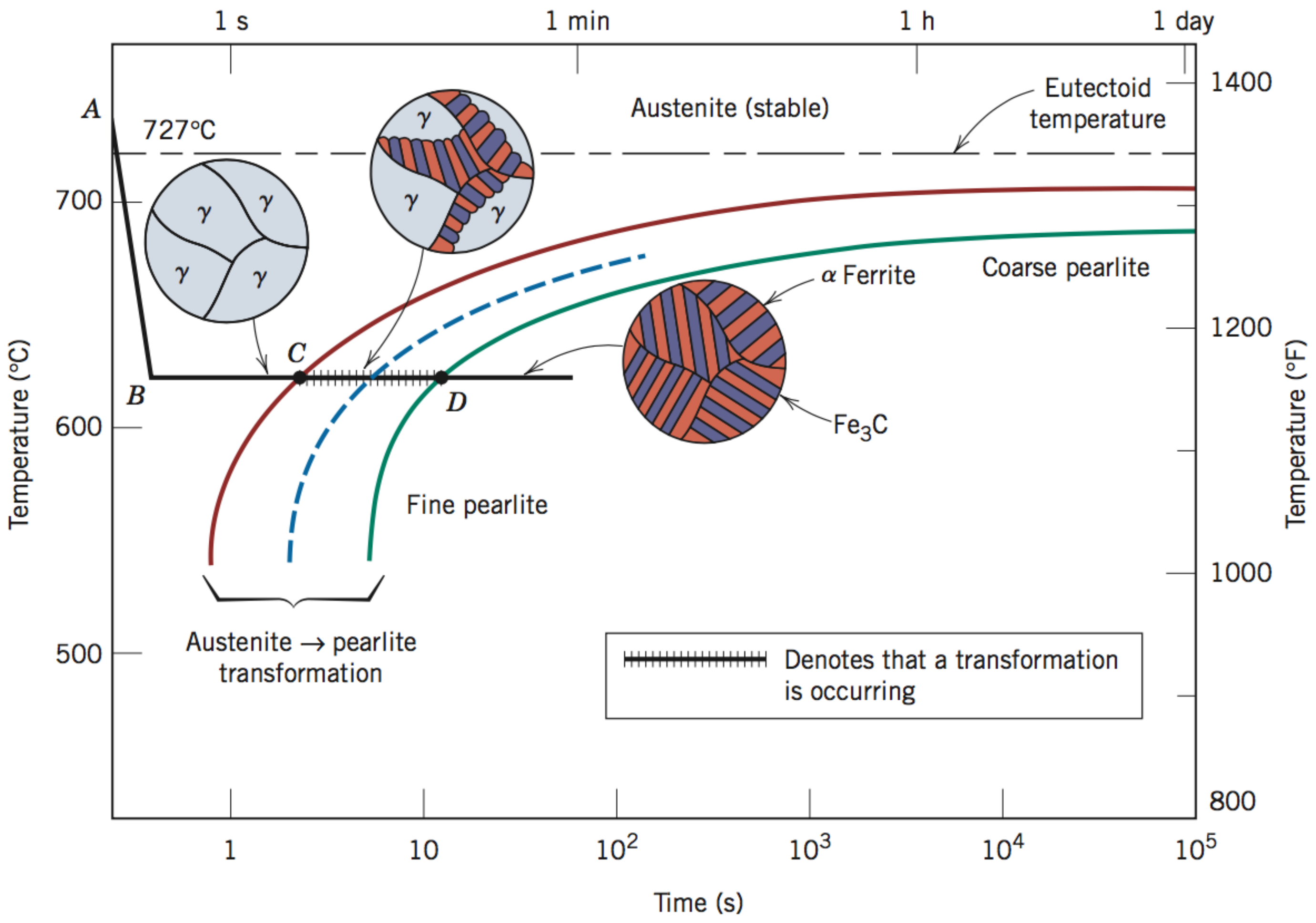
The transformation rate increases with decreasing temperature such that at 540°C, only about 3s is required for the reaction to go to 50% completion.



Austenite to Pearlite Isothermal Transformation

- Eutectoid composition, $C_0 = 0.76$ wt% C
- Begin at $T > 727$ºC
- Rapidly cool to 625ºC
- Hold T (625ºC) constant (isothermal treatment)



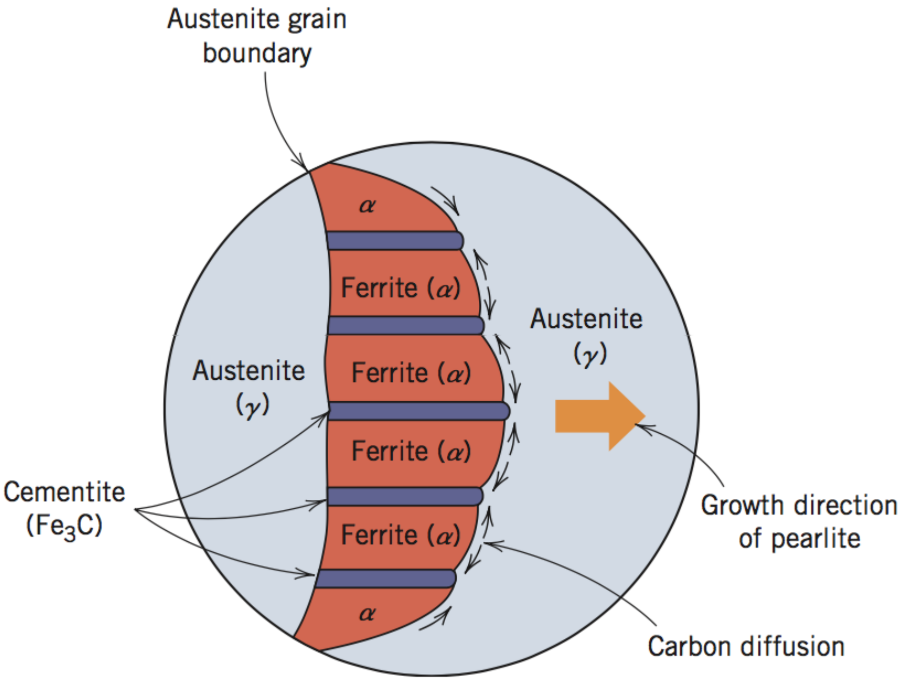


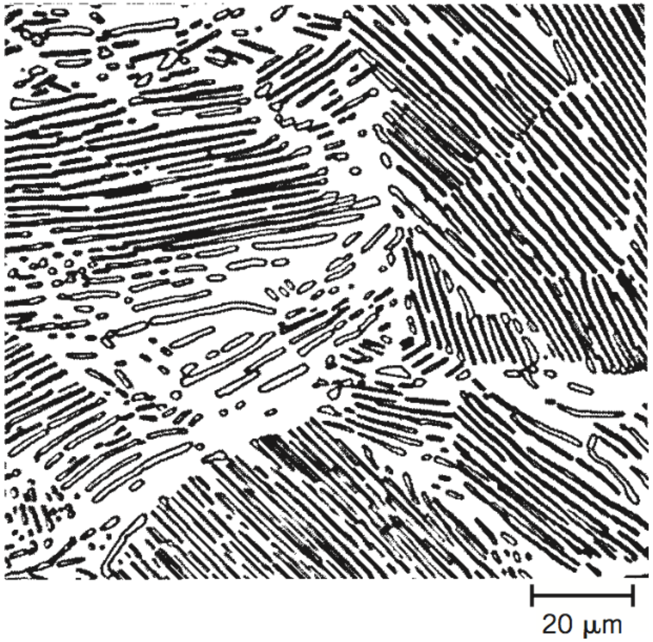
•Holding at different temperatures results in **different pearlite types**:

🔴 **Fine pearlite** forms at lower temperatures — fast nucleation, thin lamellae, harder.

🔵 **Coarse pearlite** forms at higher temperatures — slower rate, thicker lamellae, softer.

Diffusion of Carbon in Pearlite



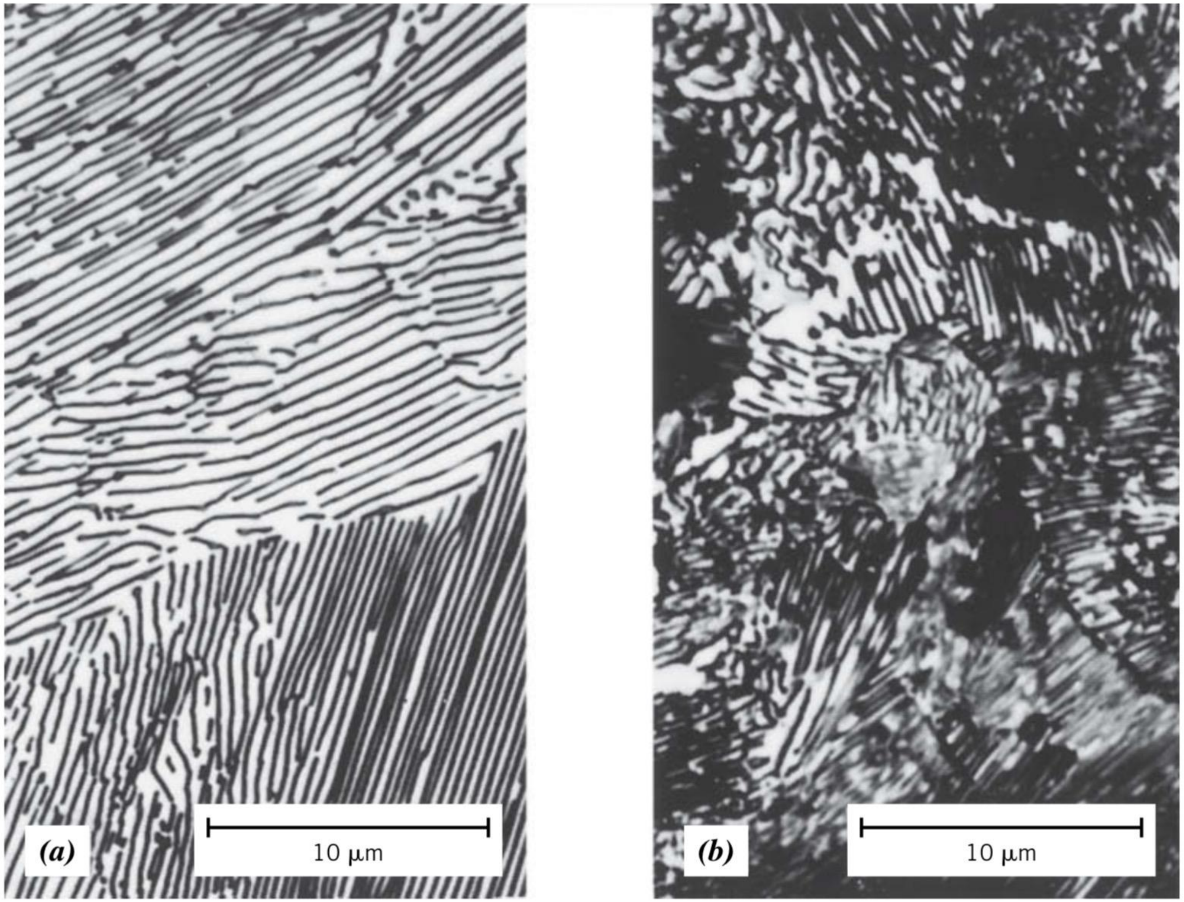


Schematic representation of the formation of pearlite from austenite.

- Direction of arrows indicates carbon diffusion.
- Fe_3C (dark)

Micrograph of eutectoid steel, showing pearlite microstructure.

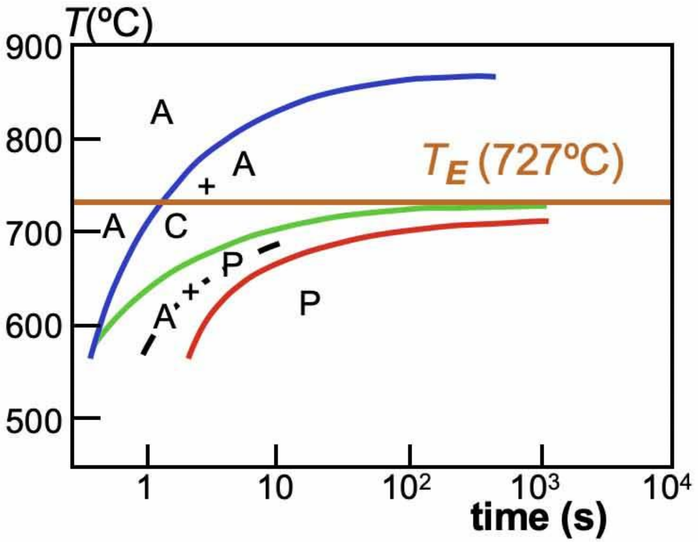
- **α** ferrite (light)
- Fe_3C (dark)



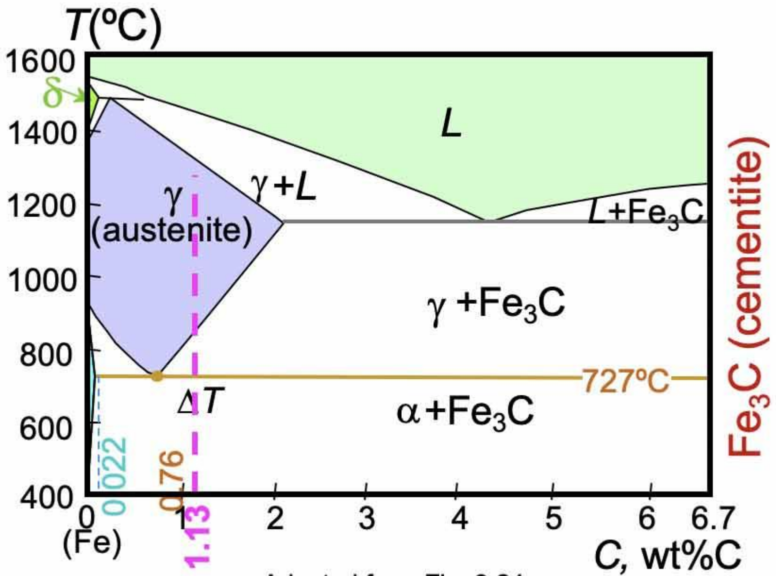
Photomicrographs of (*a*) coarse pearlite and (*b*) fine pearlite. 3000X.

Transformations Involving Noneutectoid Compositions

Consider C_0 = 1.13 wt% C



Adapted from Fig. 10.16, *Callister & Rethwisch 8e.*

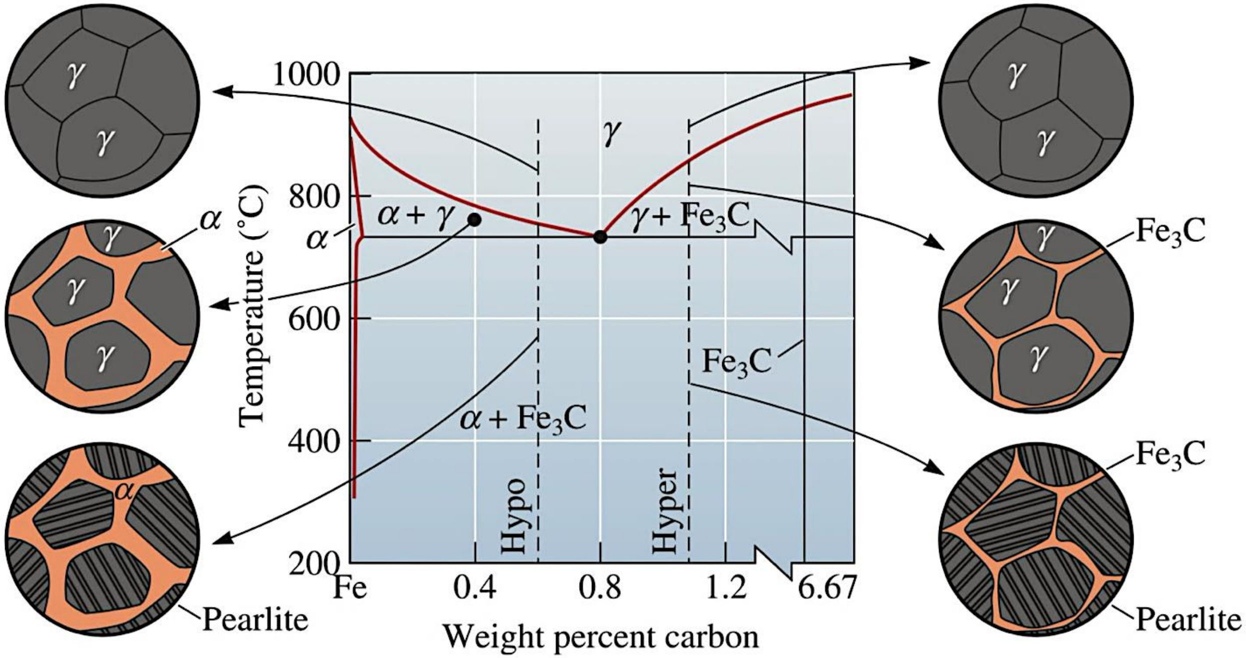


Adapted from Fig. 9.24, *Callister & Rethwisch 8e.*

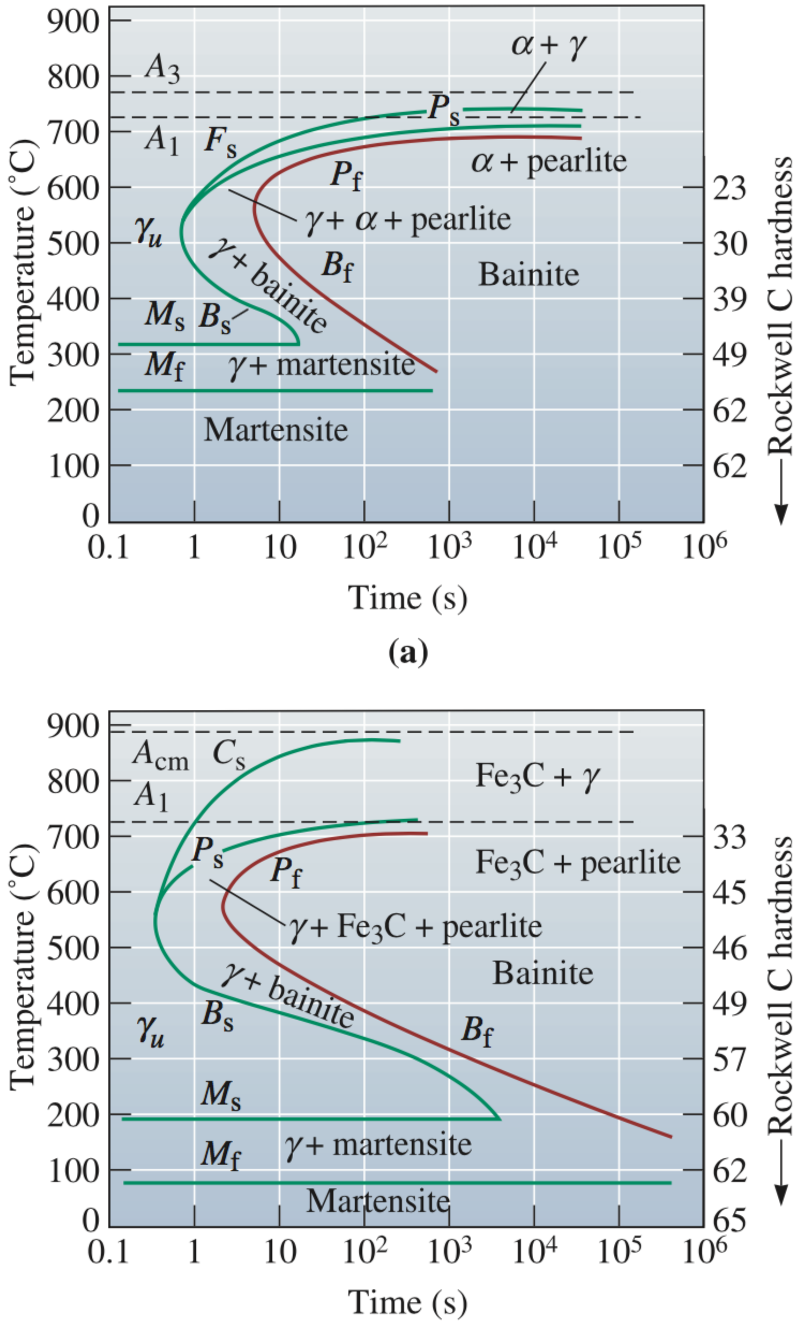
- **Hypereutectoid composition – Proeutectoid cementite**

Hypoeutectoid and Hypereutectoid Alloys

- **Hypoeutectoid steels (C < 0.76%):**
- Form **ferrite (α)** first, then **pearlite** as temperature drops.
- **Hypereutectoid steels (C > 0.76%):**
- Form **cementite (Fe_3C)** first, then **pearlite**.
- Final microstructure = **proeutectoid phase (α or Fe_3C) + pearlite**



The evolution of the microstructure of hypoeutectoid and hypereutectoid steels during cooling, in relationship to the Fe–Fe_3C phase diagram.



(a)

(b)

C = Cementite
F = Ferrite
P = Pearlite
B = Bainite
M = Martensite
s = Start
f = Finish
γ_u = Unstable Gamma Phase

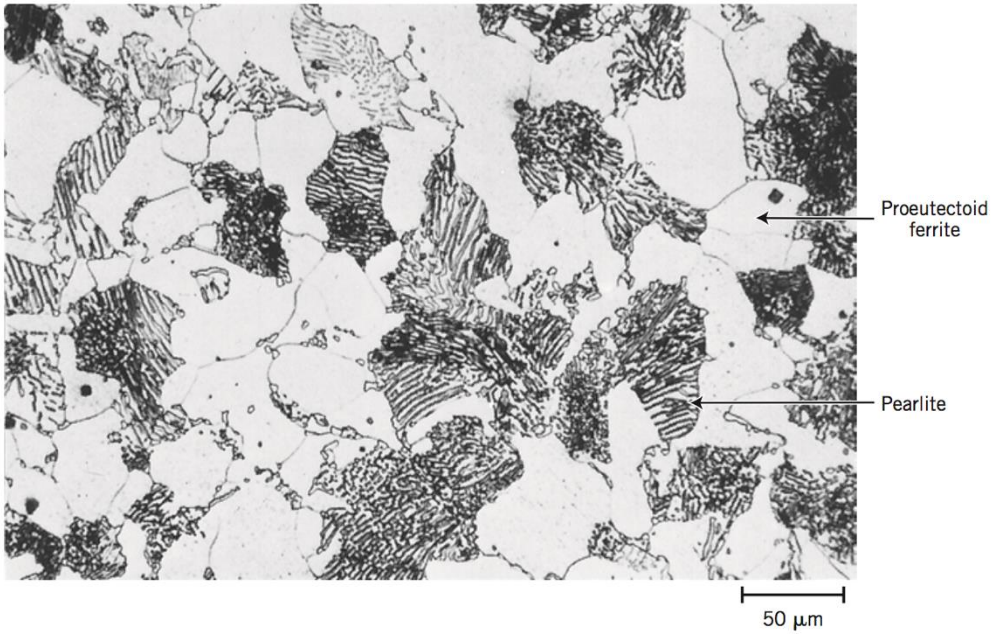
The TTT diagrams for (a) a 1050 and (b) a 10110 steel.

Time-Temperature-Transformation (TTT) Diagrams for Steels

- **TTT for 1050 Steel (a):**
- Contains mainly **pearlite**, **bainite**, and **martensite** transformation zones.
- Higher carbon leads to **harder phases** forming faster.
- **TTT for 10110 Steel (b):**
- Higher carbon content shifts curves and increases **hardness**.
- Presence of **cementite (Fe_3C)** in final structure.
- **Cooling Rate Impact:**
- **Slow cooling → pearlite**
- **Moderate cooling → bainite**
- **Rapid cooling (quenching) → martensite**
- **Hardness Scale Included:**
- Shows Rockwell C hardness increases from pearlite → bainite → martensite.

Microstructure of Hypoeutectoid Steel (0.38 wt% C)

- •**Carbon content = 0.38 wt%** → Hypoeutectoid (less than 0.76 wt%).
- •**White areas**: Proeutectoid ferrite (α) formed **before** eutectoid reaction.
- •**Dark lamellar areas**: Pearlite (α + Fe_3C) formed at 727 °C during eutectoid reaction.
- •Microstructure affects hardness and strength:
- •Ferrite → **soft and ductile**
- •Pearlite → **strong and hard**



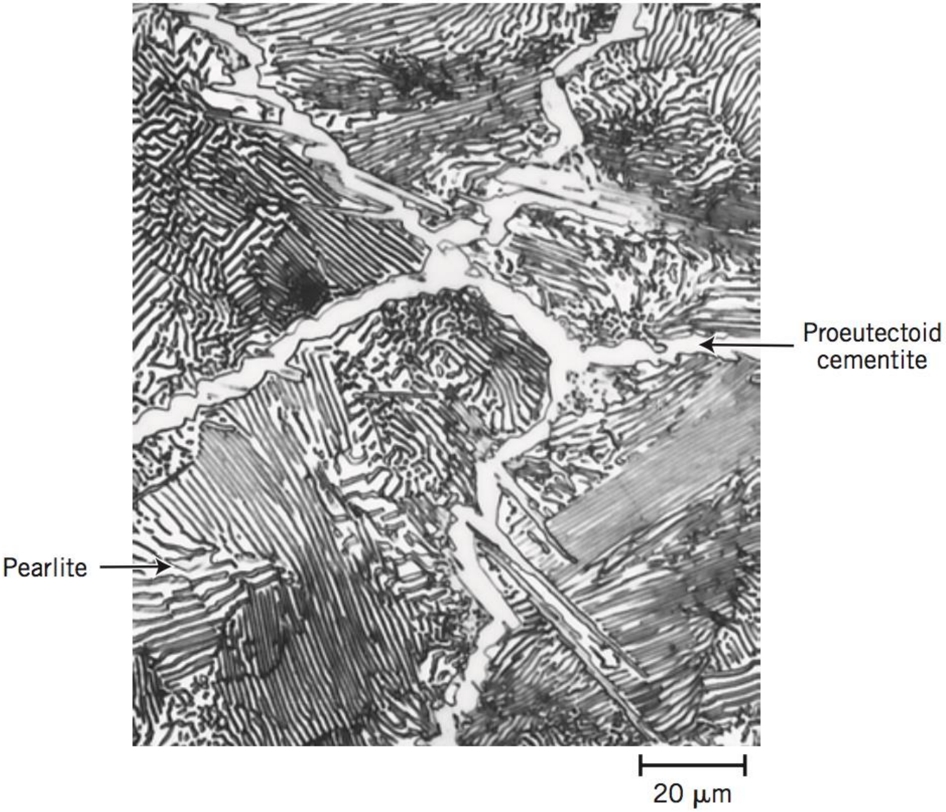
Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite.

Microstructure of 1.4 wt% C Hypereutectoid Steel

•Pearlite (dark lamellar regions):
-Formed at 727°C by eutectoid transformation of austenite.
-Provides strength and hardness.

•Proeutectoid cementite (white network):
-Forms **before** pearlite at grain boundaries.
-Appears as a white **network** surrounding pearlite colonies.
-Increases hardness but reduces toughness.

•Hypereutectoid steel:
-Carbon content > 0.76 wt%, so **cementite** forms first.

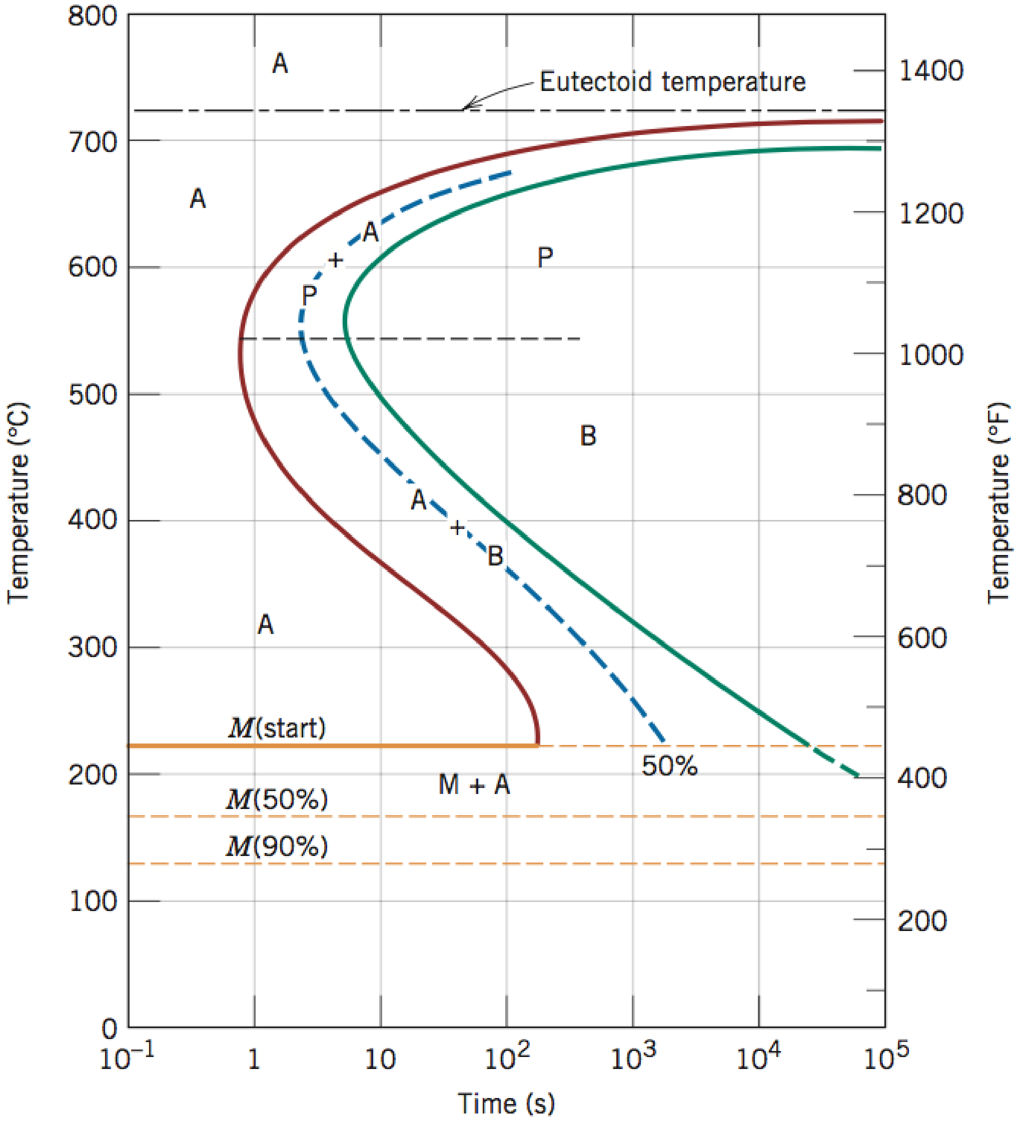


Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies.

Full TTT Diagram

The complete TTT diagram for an iron-carbon alloy of eutectoid composition.

A: austenite, B: bainite, M: martensite, P: pearlite



TTT (Time-Temperature-Transformation) Diagram

◉ Displays how **austenite** transforms into **pearlite (P)**, **bainite (B)**, or **martensite (M)** during **isothermal** cooling.

● **Austenite (A):**

-Stable above ~727°C.

-Transformation starts upon crossing the red (start) curve.

● **Pearlite Region (P):**

-Forms at higher temperatures (~600–727°C).

-Slower cooling favors pearlite.

● **Bainite Region (B):**

-Forms at **lower isothermal temperatures** (~250–550°C) when **cooling is faster than that required for pearlite**, but **not as fast as quenching for martensite**.

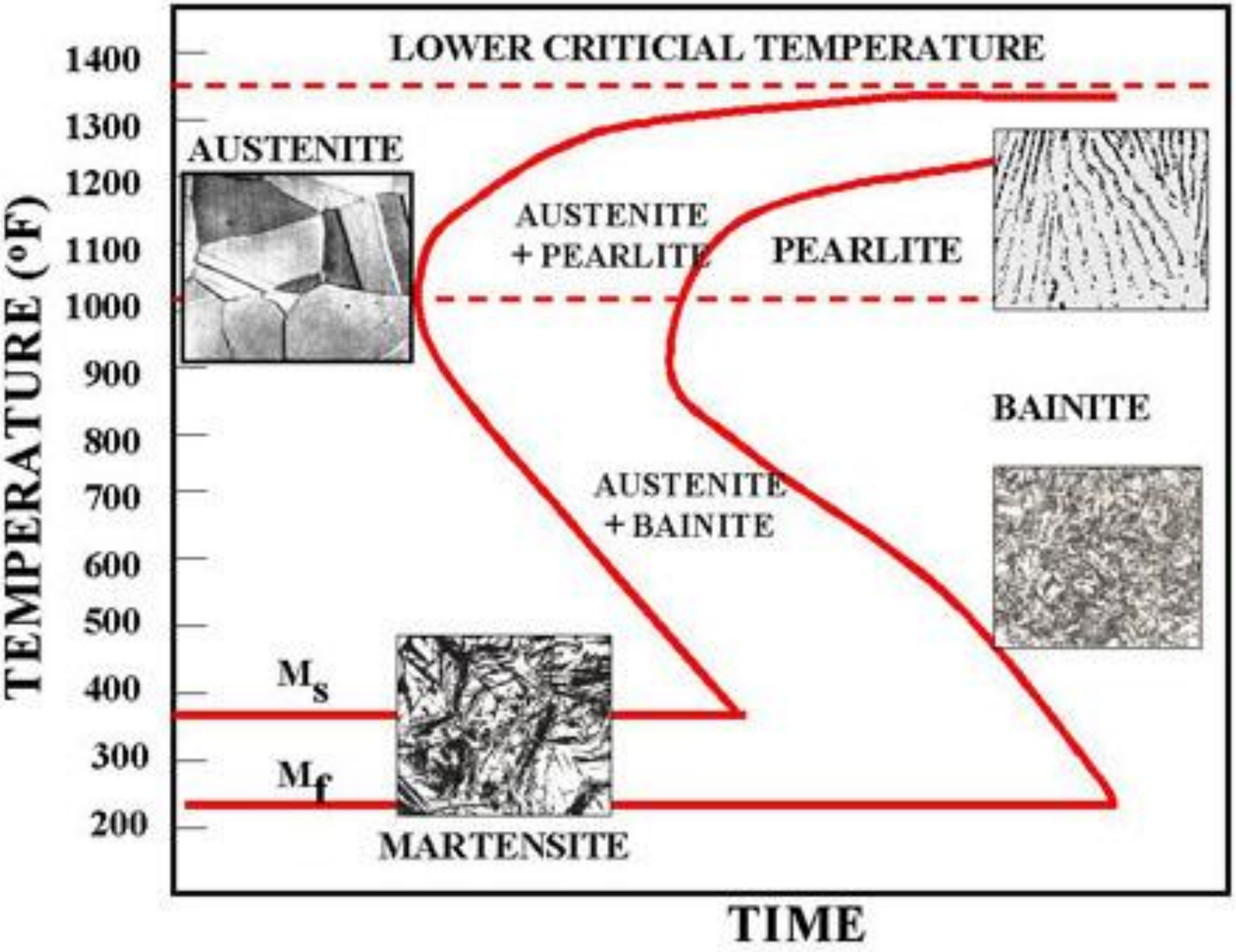
-It requires isothermal holding in the **bainitic range**, **not just moderate continuous cooling**.

● **Martensite (M):**

-Forms **below 200°C** without diffusion.

-Extremely **rapid quenching** required (bypasses nose of curve).

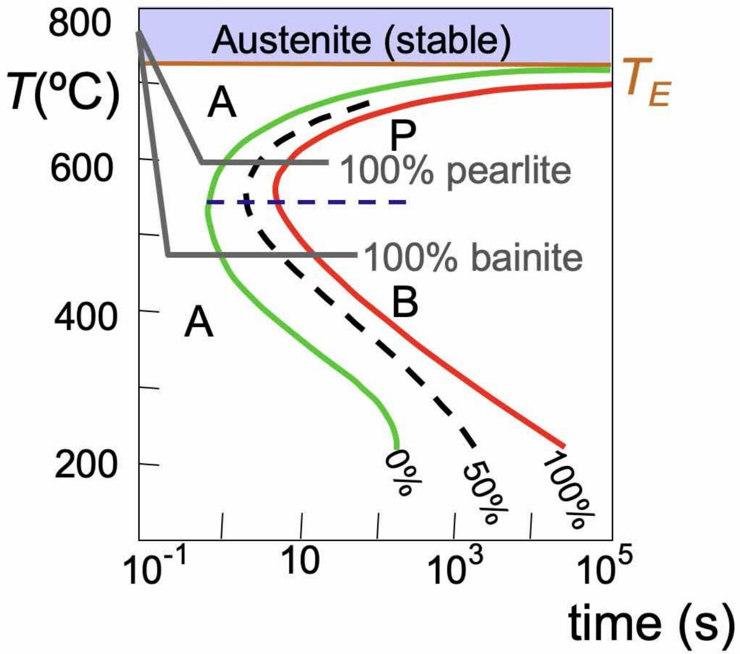
-M(start), M(50%), and M(90%) indicate transformation progress.

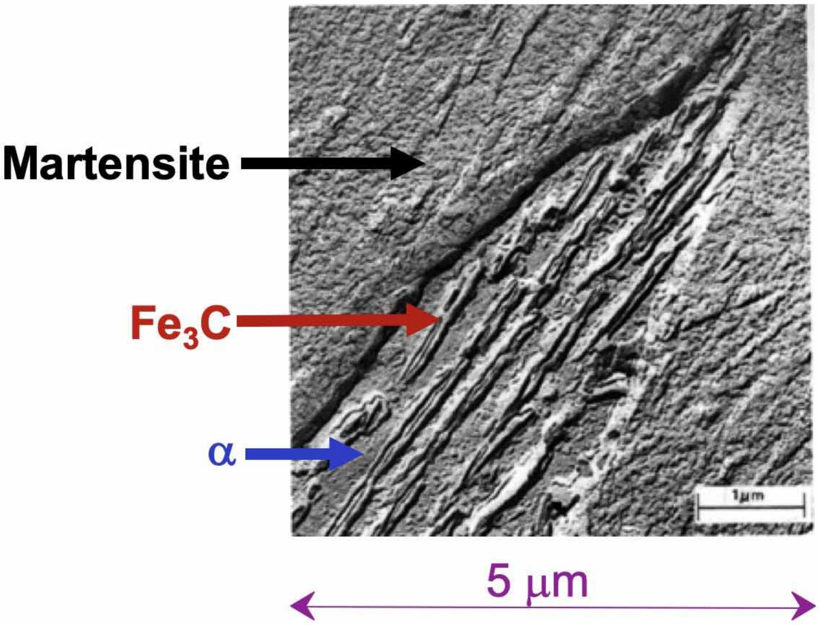


Relationship between TTT diagram and location of different microstructures.

Bainite: Another Fe-Fe_3C Transformation Product Microstructure

- Bainite:
  - -- elongated Fe_3C particles in α-ferrite matrix
  - -- diffusion controlled
- Isothermal Transf. Diagram, C_0 = 0.76 wt% C





Transmission electron micrograph showing the structure of bainite. A grain of bainite passes from lower left to upper right corners; it consists of elongated and needle-shape particles of Fe_3C within a ferrite matrix. The phase surrounding the bainite is martensite.

Formation of Bainite Microstructure

◆ **Upper Bainite** *(~300–540 °C)*

- Consists of **ferrite needles** separated by **elongated cementite particles**.
- Forms at **higher bainitic temperatures**.

◆ **Lower Bainite** *(~200–300 °C)*

- Made of **thin ferrite plates** with **fine cementite rods/blades** inside.
- Forms at **lower temperatures**, resulting in finer features.

◆ **Transformation Characteristics:**

- Controlled by **diffusion-based growth**, not nucleation.
- **Slow diffusion** at low temperatures creates **very fine microstructures**.

◆ **Note on Bainite vs Pearlite:**

- These transformations are **mutually exclusive**.
- To convert between them, the material must be **reheated to austenite** first.

Spheroidite: Another Microstructure for the Fe-Fe_3C System

◆ **How Spheroidite Forms:**

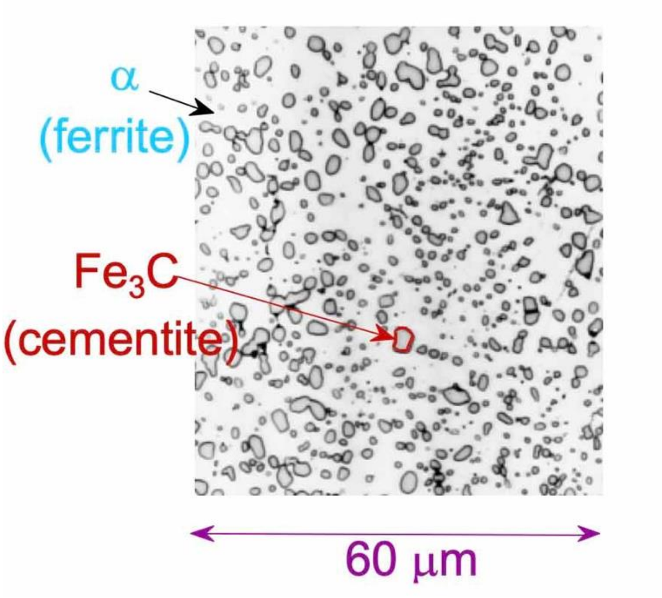
•Produced by **annealing pearlite or bainite** at temperatures just below the eutectoid (e.g., **700 °C for 24 hours**).

•**Cementite lamellae** transform into **spherical particles** within a ferrite matrix.

◆ **What Changes:**

•**Only the shape** of the cementite changes—not the composition.

•**Spheres** form to reduce surface area and interfacial energy.



Spheroidite: Another Microstructure for the Fe-Fe_3C System

◆ **Mechanism:**

- Transformation occurs via **carbon diffusion**—requires elevated temperature.
- The process is **slow**, but leads to structural softening.

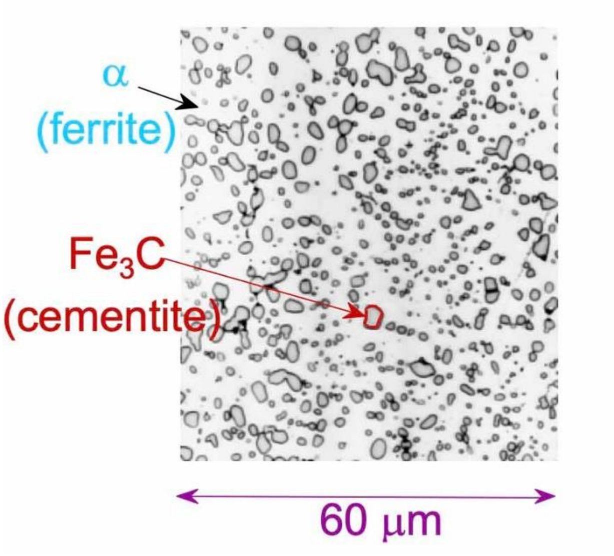
◆ **Driving Force:**

- **Reduction of total ferrite–cementite boundary area**, lowering internal energy.

◆ **Why It's Important:**

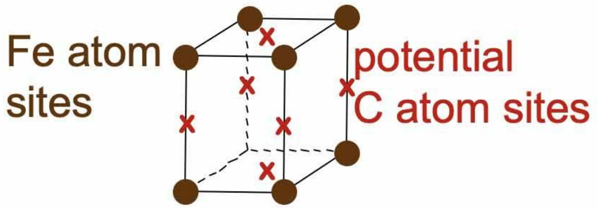
- Results in a **soft, ductile, and machinable** microstructure.
- Widely used in steels intended for **cold forming or machining applications**.

🟩 *Common in hypoeutectoid, eutectoid, and hypereutectoid steels containing pearlite or bainite.*

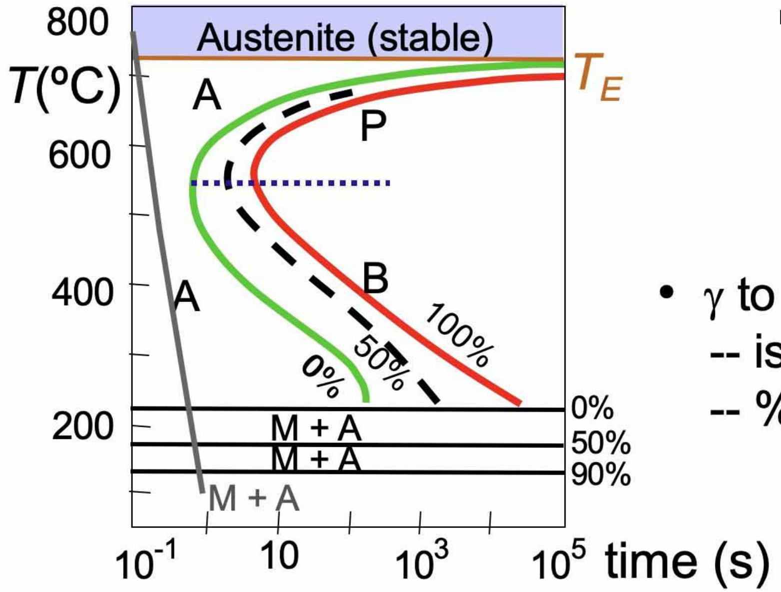


Martensite: A Nonequilibrium Transformation Product

- **Martensite**:
  -- γ(FCC) to Martensite (BCT)



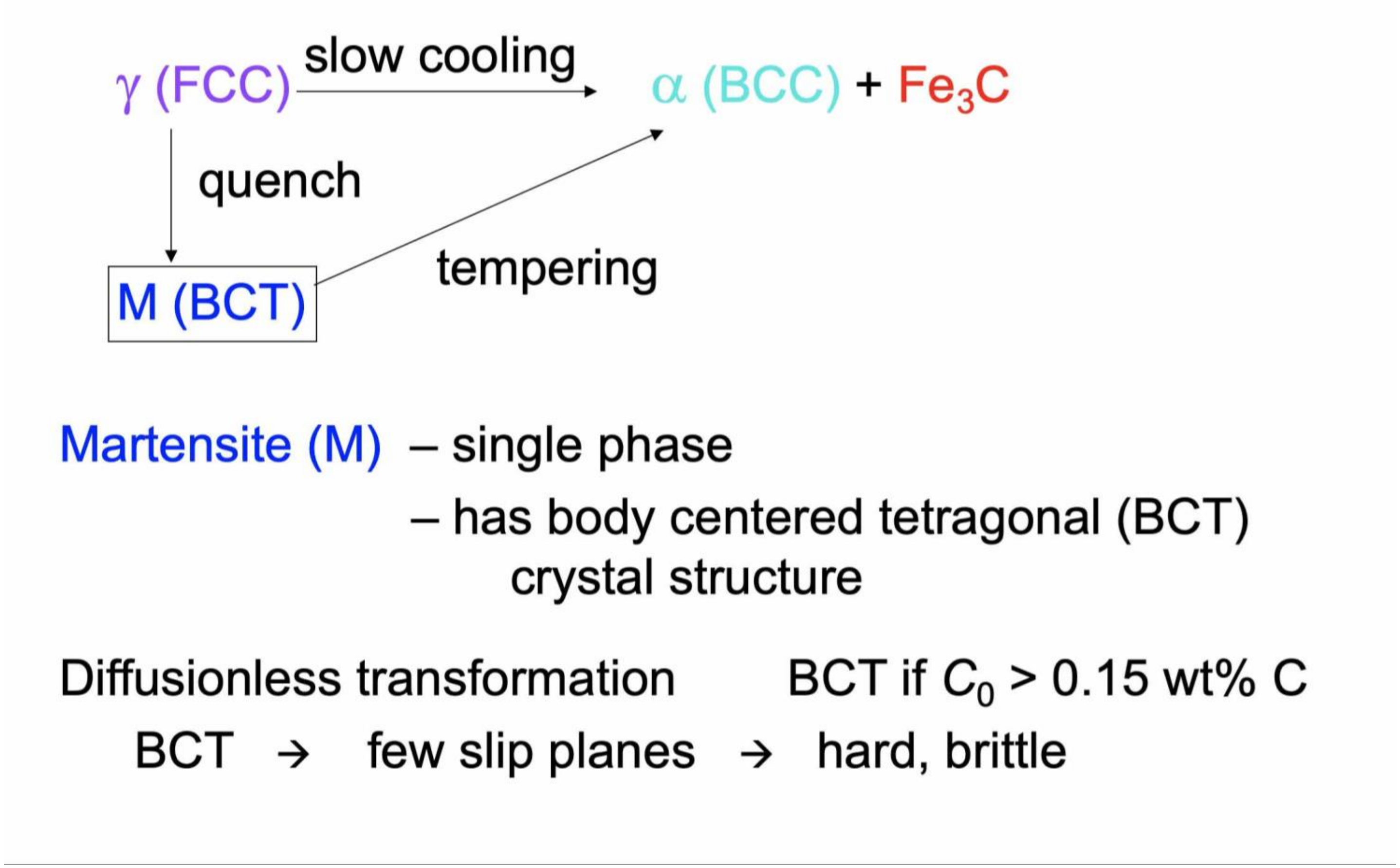
- Isothermal Transf. Diagram



▬ Martensite needles
▬ Austenite

- γ to martensite (M) transformation..
  -- is rapid! (diffusionless)
  -- % transf. depends only on *T* to which rapidly cooled

Martensite Formation Pathway



$$\begin{tikzcd}
\gamma\ (\text{FCC}) \arrow[rr, "\text{slow cooling}"] \arrow[d, "\text{quench}"] & & \alpha\ (\text{BCC}) + Fe_3C \\
\boxed{M\ (\text{BCT})} \arrow[urr, "\text{tempering}"'] & &
\end{tikzcd}$$

Martensite (M) – single phase

– has body centered tetragonal (BCT) crystal structure

Diffusionless transformation BCT if $C_0 > 0.15$ wt% C

BCT → few slip planes → hard, brittle

Martensite: Formation, Structure, and Properties

📌 Key Concepts:

- **Martensite forms** by rapid quenching of **austenite (γ, FCC)** into **martensite (BCT)**.
- **Diffusionless transformation**: No time for atomic diffusion.
- **Carbon atoms** get trapped in interstitial sites, distorting the structure.
- **Athermal transformation:** Happens instantly when critical temperature is reached.
- **Metastable phase:** Martensite remains at room temp but can revert on heating.

📊 Microstructure:

- **Martensite appears as needle-like structures**.
- Micrograph shows black **martensite needles** in a light **austenite matrix** (scale = 60 μm).

Martensite: Formation, Structure, and Properties

📈 TTT Diagram Insight:

- Martensite forms **below ~250°C**, bypassing pearlite and bainite regions.
- **% transformation** depends only on **final quench temperature (T)**, **not time**.
- Not shown in Fe–C diagram since it's a nonequilibrium phase.
- Formed **without diffusion** — rapid cooling prevents nucleation of pearlite or bainite.

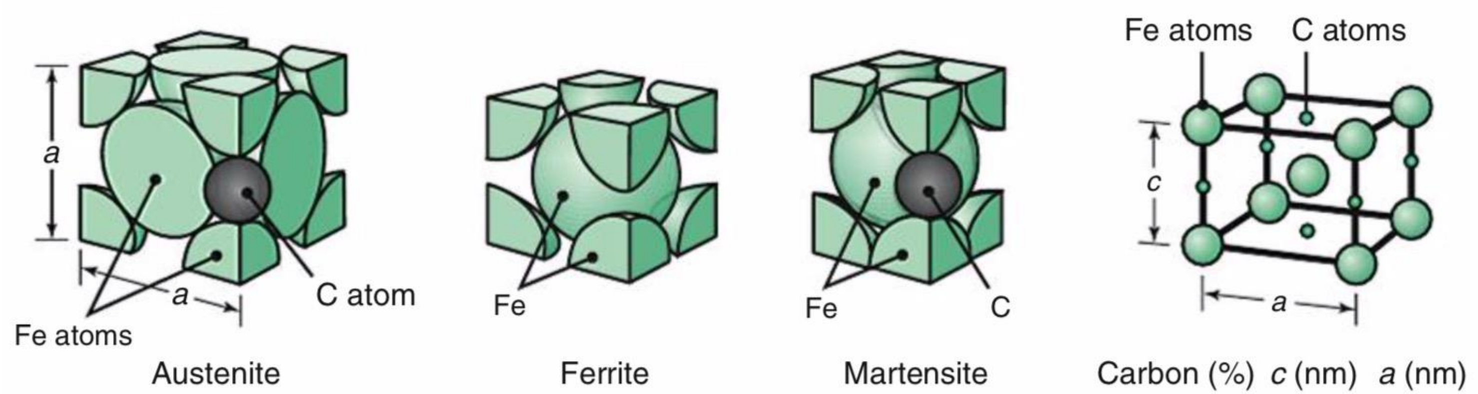
✅ Characteristics:

- Very **hard and brittle** due to trapped carbon.
- **Non-equilibrium product**—requires **tempering** for ductility.
- Requires tempering to improve toughness and relieve internal stresses.

Martensite Crystal Structure: BCT Distortion Due to Carbon

📐 Unit Cell Comparison: Austenite → Martensite

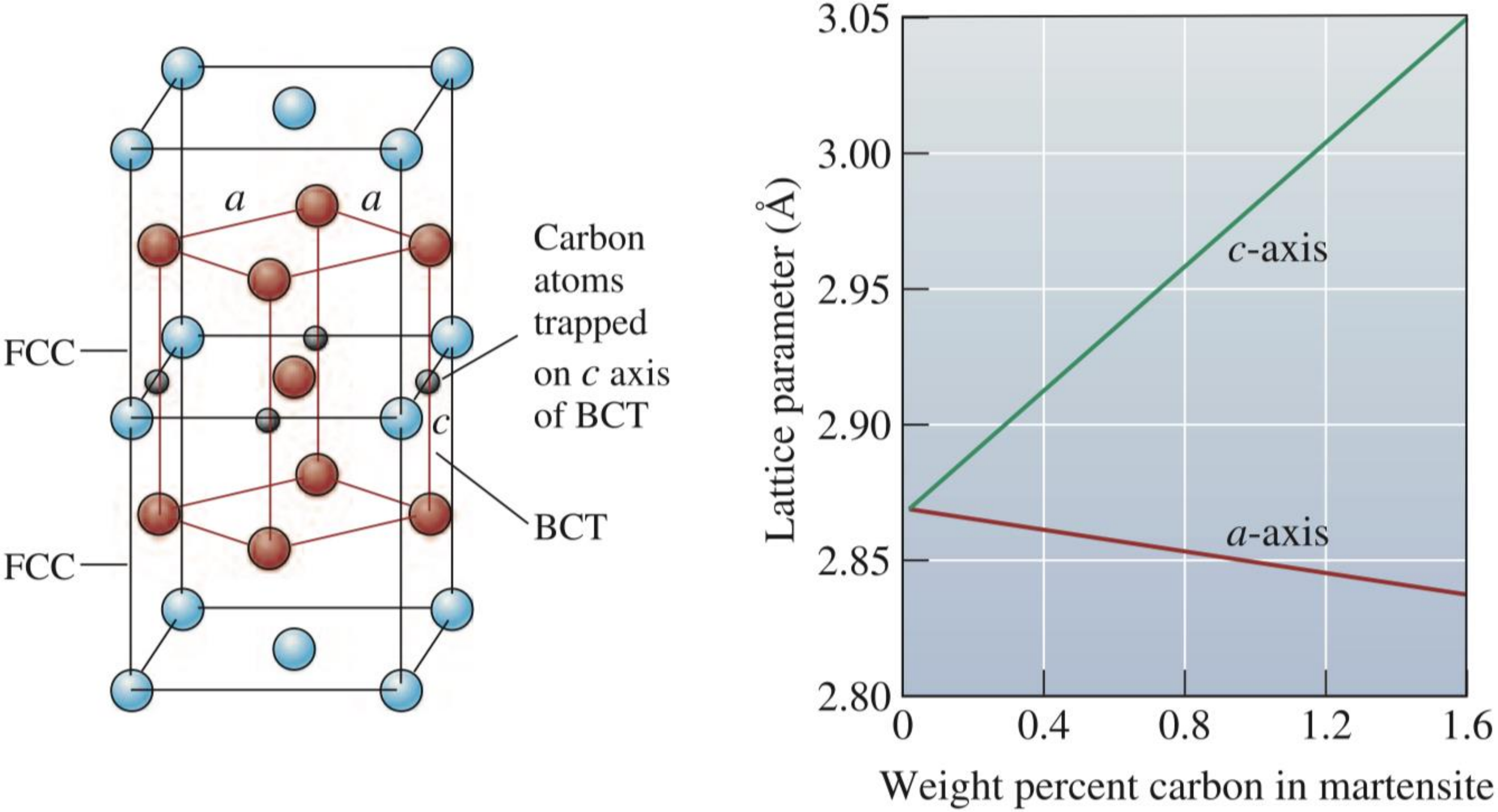
- **Austenite (γ-FCC)**: Carbon dissolves interstitially without major lattice distortion.
- **Ferrite (α-BCC)**: Low carbon solubility; carbon is largely absent.
- **Martensite (BCT)**:
- Forms via **diffusionless transformation**.
- **Carbon atoms trapped** → lattice distorts → Body-Centered **Tetragonal**.
- As **carbon increases**, c/a ratio increases (see table).
- This distortion causes **high hardness** and **low ductility**.



Carbon (%)	c (nm)	a (nm)
0	0.286	0.286
0.20	0.288	0.2858
0.40	0.291	0.2856

Martensite Structure and Carbon Effects

- Low-carbon steels (< 0.2%C): Martensite forms with BCC structure.
- High-carbon steels: Martensite forms with BCT (Body-Centered Tetragonal) structure.
- BCT distortion is caused by **carbon atoms trapped** in interstitial sites during rapid quenching.
- As carbon content increases, **c-axis elongates**, increasing **tetragonality** and hardness.



(a) **(b)**

Figure 12-24 (a) The unit cell of BCT martensite is related to the FCC austenite unit cell. (b) As the percentage of carbon increases, more interstitial sites are filled by the carbon atoms, and the tetragonal structure of the martensite becomes more pronounced.

Atomic-Level Mechanism of Martensite Transformation

Explanation:

- Carbon atoms in austenite (FCC) occupy interstitial positions (½, 0, 0).
- During rapid cooling, these atoms are **trapped** as lattice shifts to BCC/BCT.
- The transformation is **diffusionless (athermal)** — no atomic rearrangement occurs.
- This causes lattice distortion → high internal stress → hardness.

Martensite Start (Ms) and Finish (Mf) Temperatures

Important Facts:

- Transformation begins below **Ms ≈ 220°C**.
- Martensite fraction increases with further cooling until **Mf** is reached.
- At Mf: ~100% martensite forms.
- Martensite **amount depends only on temperature**, not on holding time.

Composition Consistency During Transformation

Core Concept:

- Martensite retains the **same composition** as the parent austenite.
- No long-range diffusion → no change in chemistry.
- Martensite transformation follows the principle of **mass conservation**.

Case Example – Dual-Phase Steel

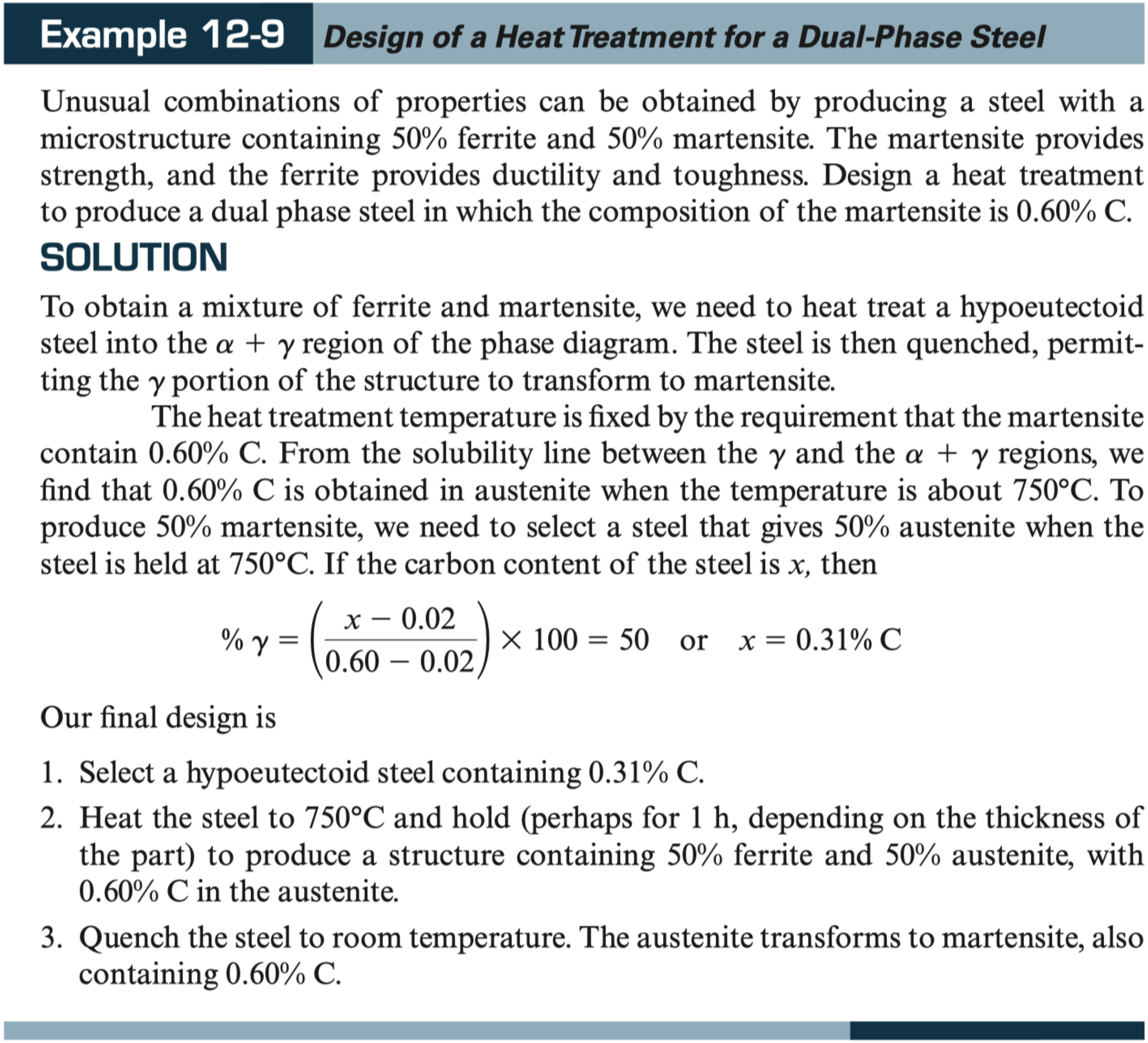
Application:

•A heat treatment can partially transform austenite to martensite.

•Remaining austenite transforms to ferrite upon slow cooling.

•This results in **dual-phase microstructure** (martensite + ferrite) → combines strength & ductility.

•Used in **automotive components**, structural steels.



Example 12-9 *Design of a Heat Treatment for a Dual-Phase Steel*

Unusual combinations of properties can be obtained by producing a steel with a microstructure containing 50% ferrite and 50% martensite. The martensite provides strength, and the ferrite provides ductility and toughness. Design a heat treatment to produce a dual phase steel in which the composition of the martensite is 0.60% C.

SOLUTION

To obtain a mixture of ferrite and martensite, we need to heat treat a hypoeutectoid steel into the $\alpha + \gamma$ region of the phase diagram. The steel is then quenched, permitting the γ portion of the structure to transform to martensite.

The heat treatment temperature is fixed by the requirement that the martensite contain 0.60% C. From the solubility line between the γ and the $\alpha + \gamma$ regions, we find that 0.60% C is obtained in austenite when the temperature is about 750°C. To produce 50% martensite, we need to select a steel that gives 50% austenite when the steel is held at 750°C. If the carbon content of the steel is x, then

$$\%\,\gamma = \left(\frac{x - 0.02}{0.60 - 0.02}\right) \times 100 = 50 \quad \text{or} \quad x = 0.31\%\ \text{C}$$

Our final design is

1. Select a hypoeutectoid steel containing 0.31% C.
2. Heat the steel to 750°C and hold (perhaps for 1 h, depending on the thickness of the part) to produce a structure containing 50% ferrite and 50% austenite, with 0.60% C in the austenite.
3. Quench the steel to room temperature. The austenite transforms to martensite, also containing 0.60% C.

[Example adopted from Askeland 7e, page 444]

Effect of Alloying on Transformation Kinetics

📌 **Effect of Alloying Elements**

Alloying elements can shift phase transformation temperatures and slow down transformations.

Key Alloying Elements:

•**Cr, Ni, Mo, Si, Mn**

-These elements **retard the transformation**

γ (austenite) → α (ferrite) + Fe_3C (cementite)

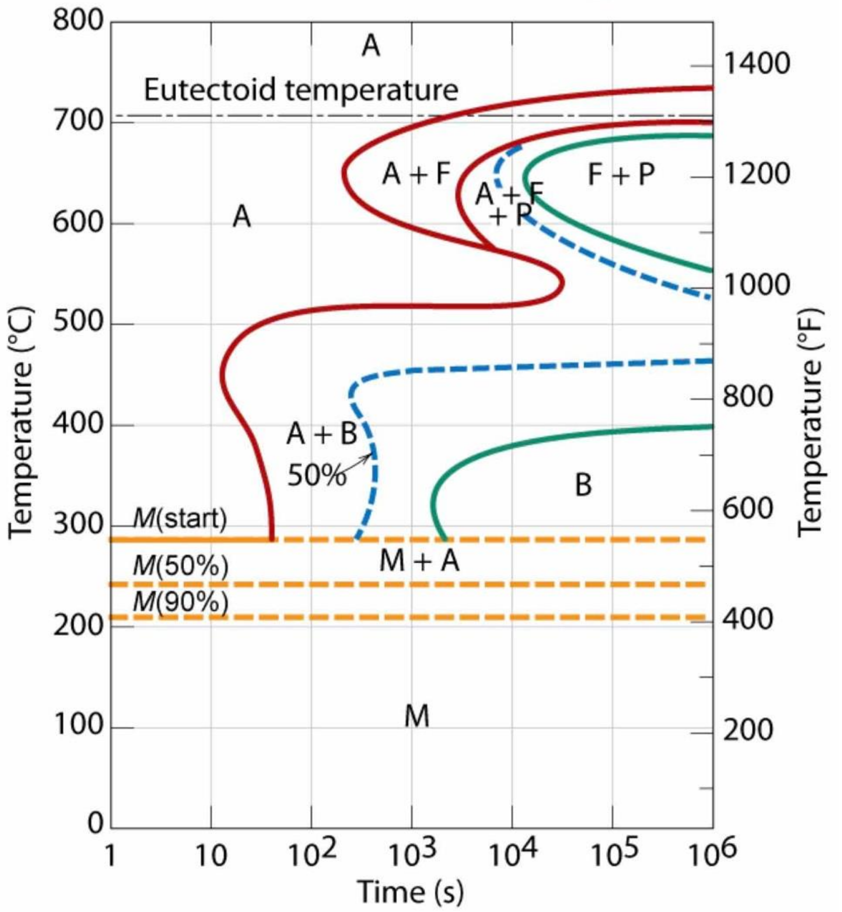
-This **delays pearlite and bainite formation** during cooling.

📈 **TTT Diagram Insight:**

•Alloying shifts **TTT curves to the right**, increasing hardenability.

•Martensite (M) forms if the cooling curve avoids the pearlite/bainite noses.

•Dashed and solid lines represent different alloy compositions.



Continuous Cooling Transformation Diagrams (CCT): Real Cooling Behavior

📘 **Concept Overview:**

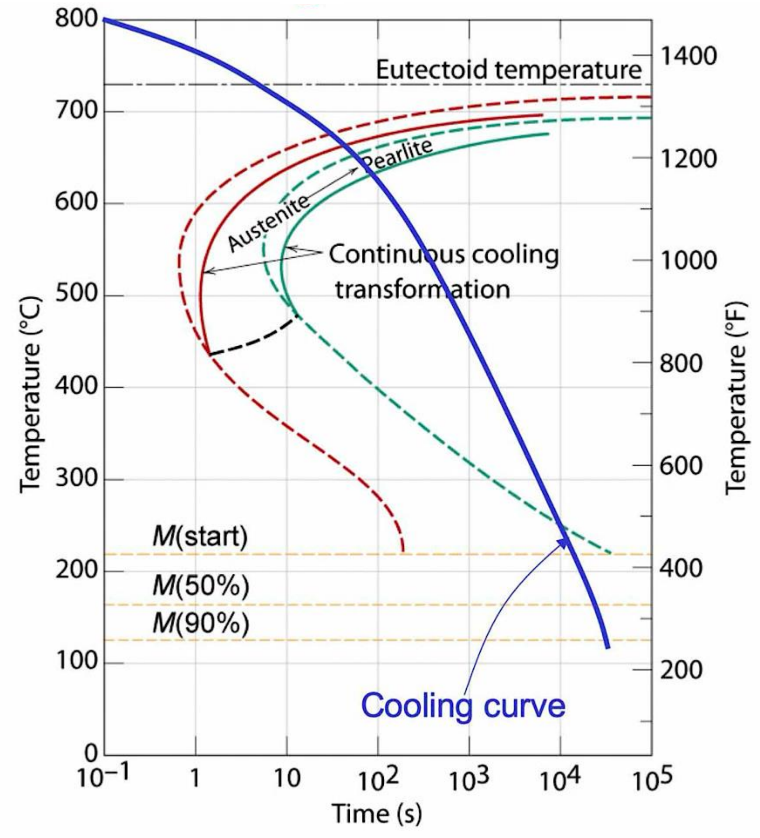
- TTT diagrams assume **isothermal transformation** (constant temperature), which is idealized and rarely practical.
- **CCT diagrams** model transformation under **real cooling conditions**, where temperature decreases continuously with time.

🔁 **Transformation Path:**

- The **blue cooling curve** intersects the CCT lines to show which microstructure (pearlite, bainite, or martensite) will form.
- If the cooling rate is fast enough to **bypass pearlite/bainite regions**, **martensite** will form.

📊 **Key Differences:**

- CCT diagrams shift transformation start/end to **longer times** compared to TTT diagrams.
- They are essential for **predicting microstructure** in actual processes like air cooling, oil quenching, etc.



Effect of Cooling Rate on Transformation Products (CCT Diagram)

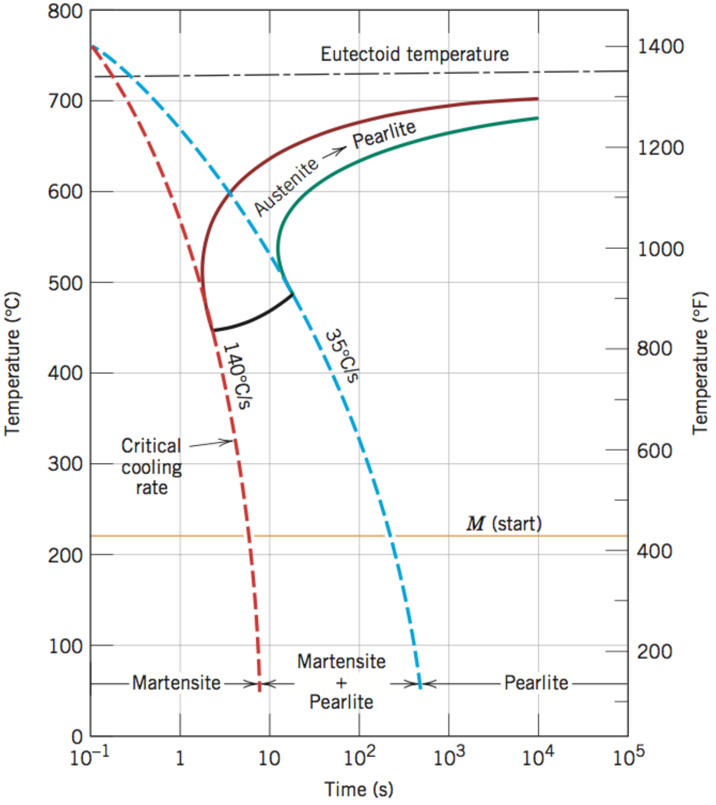
📘 **Understanding the Diagram:**

•This **Continuous Cooling Transformation (CCT)** diagram shows how different **cooling rates** affect the microstructure of a **eutectoid steel**.

•Two cooling curves are superimposed:

🔴 Red line = **Moderately fast cooling (140°C/s)** → forms **martensite + pearlite**.

🔵 Blue line = **Slow cooling (35°C/s)** → forms mostly **pearlite**.



Effect of Cooling Rate on Transformation Products (CCT Diagram)

⚠ **Critical Cooling Rate**:

•The **minimum cooling rate** required to avoid diffusion-controlled products (like pearlite) and form **100% martensite**.

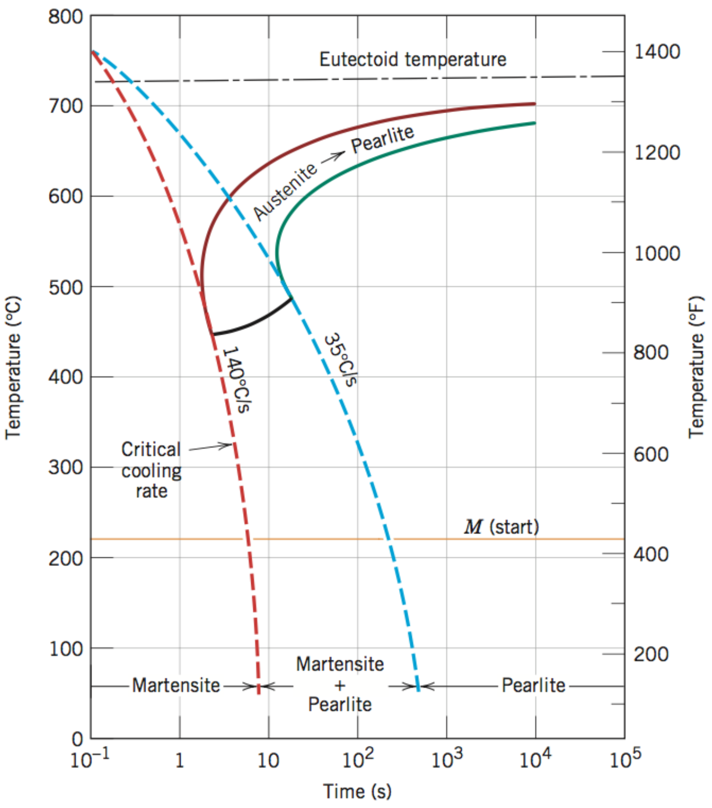
•If cooling is **slower** than this rate, **partial or no martensite** will form.

•✅ **Learning Points:**

•Martensite forms **only if** the cooling curve **misses the nose** of the pearlite/bainite region.

•Faster cooling increases the chance of martensite formation.

•Engineers use this knowledge to design **heat treatment processes** for desired hardness/toughness.



Microstructure Evolution vs. Cooling Rate

📉 Cooling Rate Controls Transformation Path

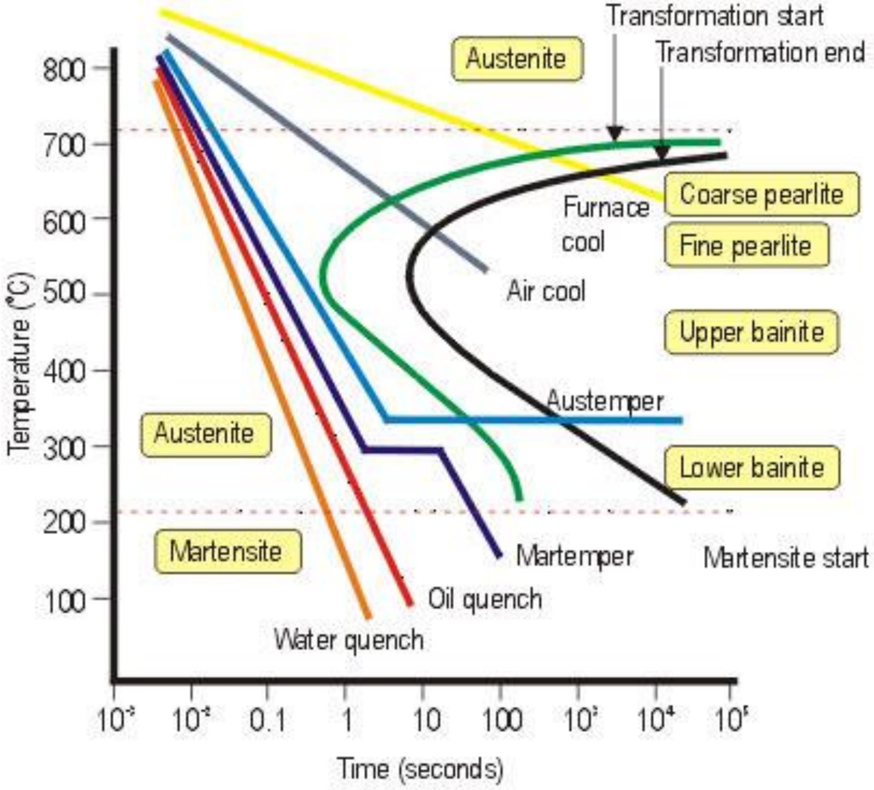
- Different cooling paths from austenite yield different microstructures.
- Fastest (e.g., **water quench**) → **100% martensite**.
- Intermediate (e.g., **austempering**) → **upper/lower bainite**.
- Slow (e.g., **air/furnace cool**) → **fine/coarse pearlite**.

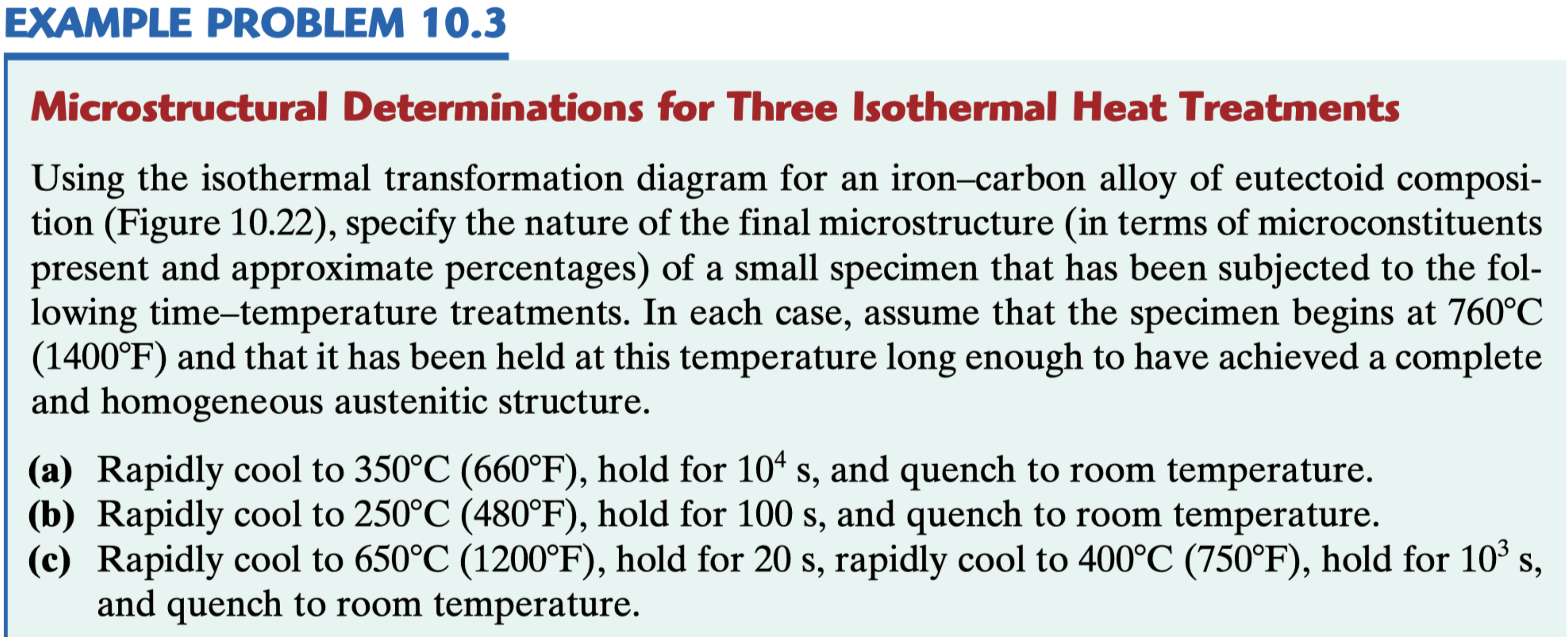
🧊 Quenching Media Impact

- **Water** → Very fast cooling → Martensite.
- **Oil** → Slightly slower → Martensite + Bainite.
- **Air/Furnace** → Slow cooling → Pearlite forms.

📌 Austempering & Martempering

- **Austempering**: Hold in bainite region → improves toughness.
- **Martempering**: Hold just above Ms (martensite start) to reduce thermal stress and cracking.





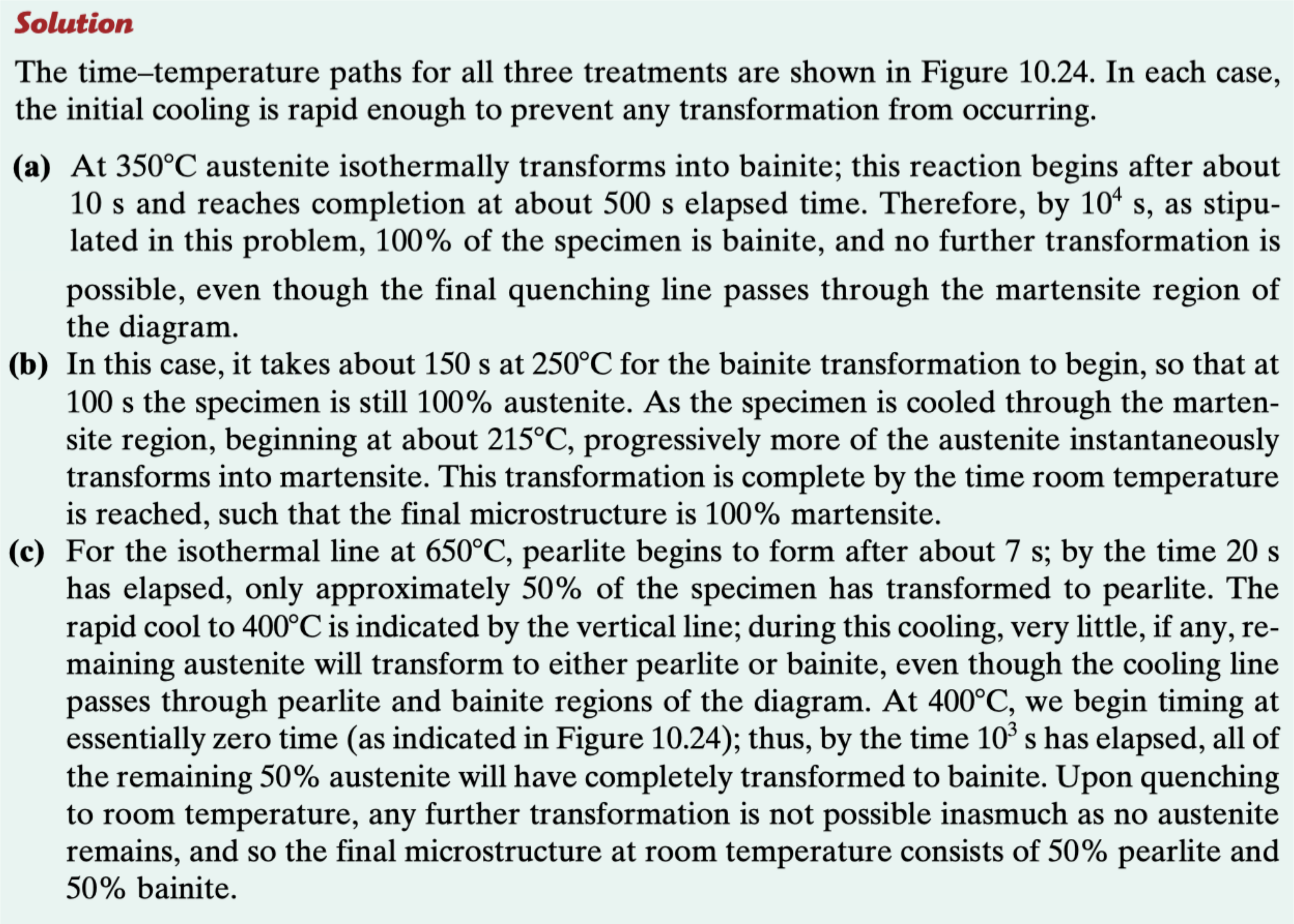
EXAMPLE PROBLEM 10.3

Microstructural Determinations for Three Isothermal Heat Treatments

Using the isothermal transformation diagram for an iron–carbon alloy of eutectoid composition (Figure 10.22), specify the nature of the final microstructure (in terms of microconstituents present and approximate percentages) of a small specimen that has been subjected to the following time–temperature treatments. In each case, assume that the specimen begins at 760°C (1400°F) and that it has been held at this temperature long enough to have achieved a complete and homogeneous austenitic structure.

(a) Rapidly cool to 350°C (660°F), hold for 10^4 s, and quench to room temperature.
(b) Rapidly cool to 250°C (480°F), hold for 100 s, and quench to room temperature.
(c) Rapidly cool to 650°C (1200°F), hold for 20 s, rapidly cool to 400°C (750°F), hold for 10^3 s, and quench to room temperature.

[Example adopted from Callister 9e, page 379]



Solution

The time–temperature paths for all three treatments are shown in Figure 10.24. In each case, the initial cooling is rapid enough to prevent any transformation from occurring.

(a) At 350°C austenite isothermally transforms into bainite; this reaction begins after about 10 s and reaches completion at about 500 s elapsed time. Therefore, by 10^4 s, as stipulated in this problem, 100% of the specimen is bainite, and no further transformation is possible, even though the final quenching line passes through the martensite region of the diagram.

(b) In this case, it takes about 150 s at 250°C for the bainite transformation to begin, so that at 100 s the specimen is still 100% austenite. As the specimen is cooled through the martensite region, beginning at about 215°C, progressively more of the austenite instantaneously transforms into martensite. This transformation is complete by the time room temperature is reached, such that the final microstructure is 100% martensite.

(c) For the isothermal line at 650°C, pearlite begins to form after about 7 s; by the time 20 s has elapsed, only approximately 50% of the specimen has transformed to pearlite. The rapid cool to 400°C is indicated by the vertical line; during this cooling, very little, if any, remaining austenite will transform to either pearlite or bainite, even though the cooling line passes through pearlite and bainite regions of the diagram. At 400°C, we begin timing at essentially zero time (as indicated in Figure 10.24); thus, by the time 10^3 s has elapsed, all of the remaining 50% austenite will have completely transformed to bainite. Upon quenching to room temperature, any further transformation is not possible inasmuch as no austenite remains, and so the final microstructure at room temperature consists of 50% pearlite and 50% bainite.

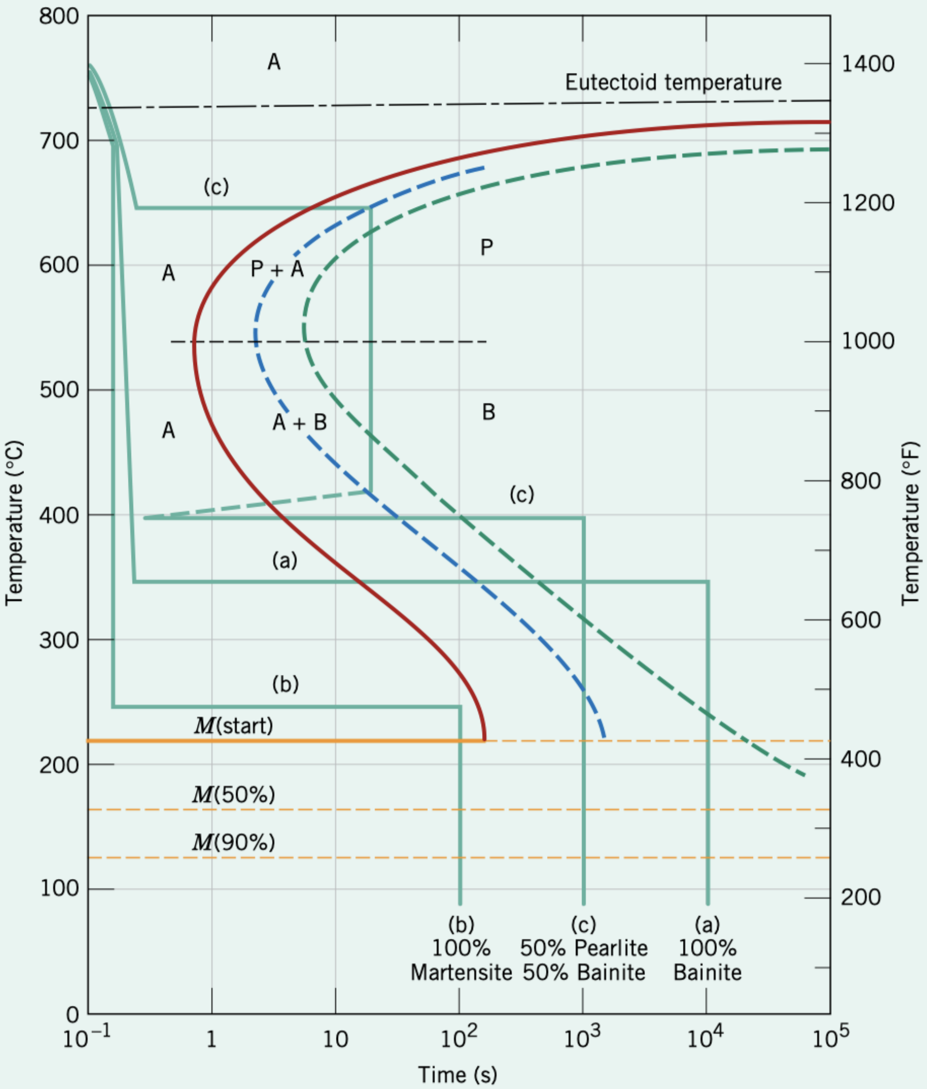
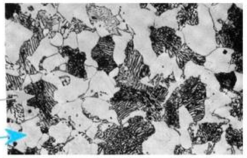


Figure 10.24 Isothermal transformation diagram for an iron–carbon alloy of eutectoid composition and the isothermal heat treatments (a), (b), and (c) in Example Problem 10.3.

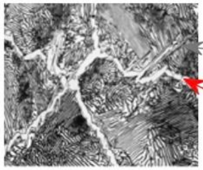
Mechanical Properties: Effect of Carbon Content in Steel



Adapted from Fig. 9.30, *Callister & Rethwisch 8e.*

$C_0 < 0.76$ wt% C

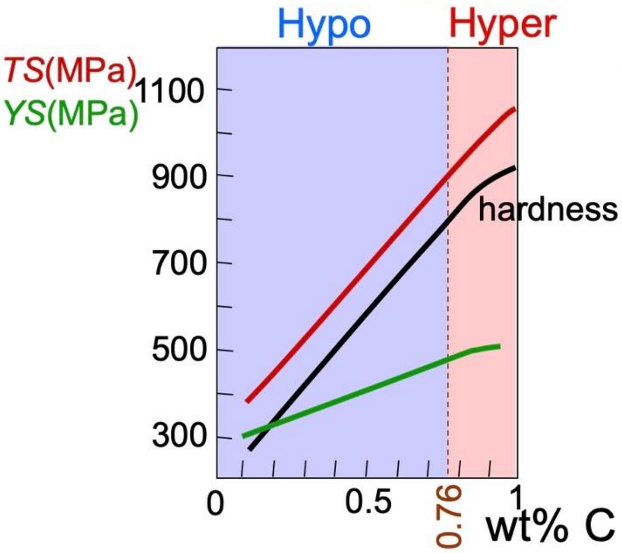
Hypoeutectoid

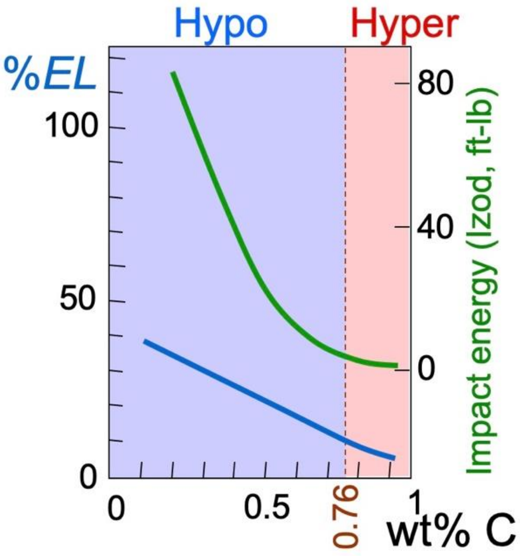


$C_0 > 0.76$ wt% C

Hypereutectoid

Adapted from Fig. 9.33, *Callister & Rethwisch 8e.*

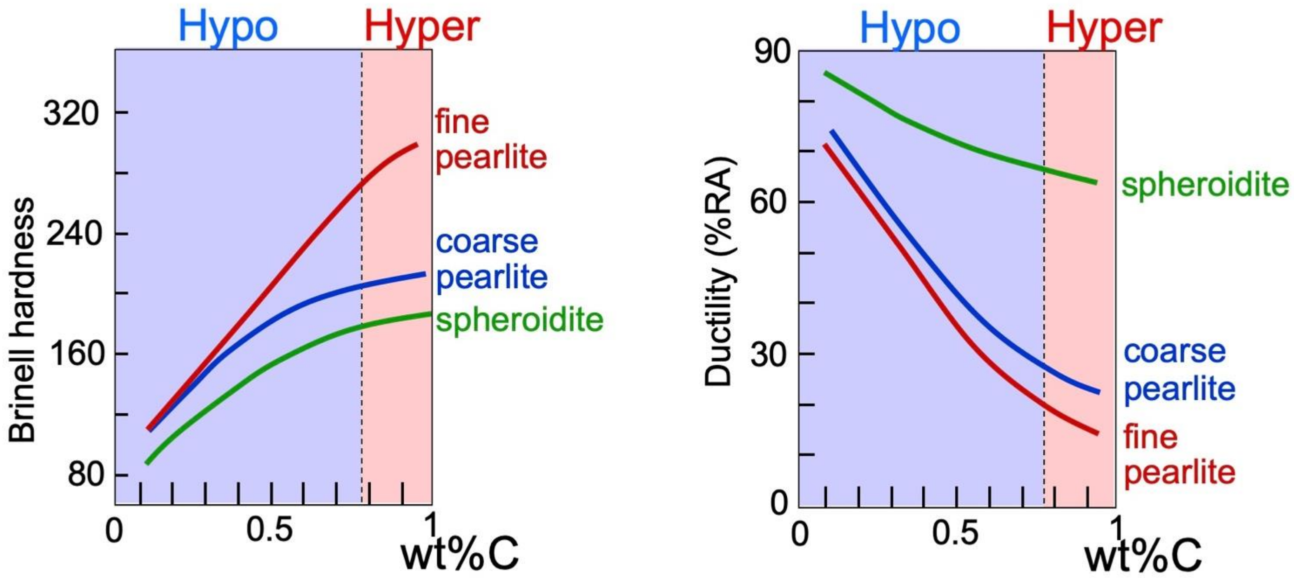




Adapted from Fig. 10.29, *Callister & Rethwisch 8e.* (Fig. 10.29 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, p. 9.)

- Increase C content: *TS* and *YS* increase, %*EL* decreases

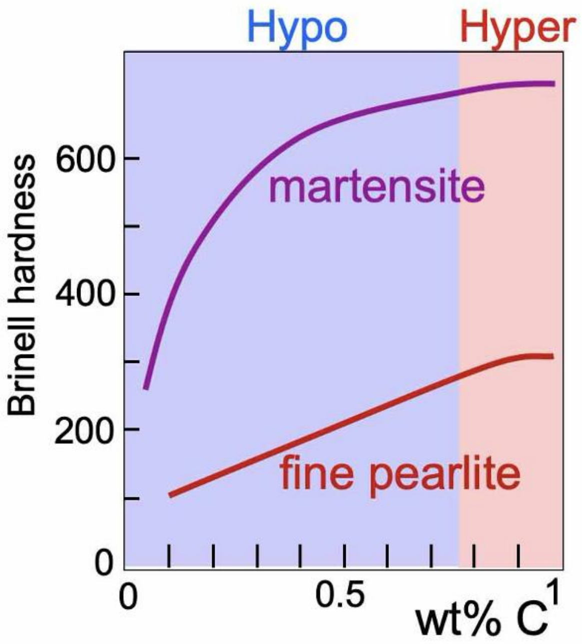
Mechanical Properties of Pearlite and Spheroidite in Steels



- Hardness: fine > coarse > spheroidite
- %RA: fine < coarse < spheroidite

Adapted from Fig. 10.30, *Callister & Rethwisch 8e.* (Fig. 10.30 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, pp. 9 and 17.)

Mechanical Properties of Pearlite and Martensite in Steels

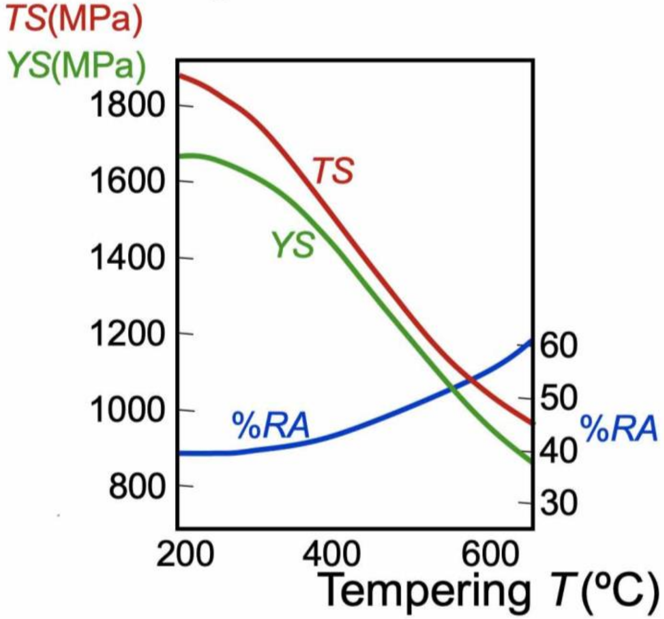


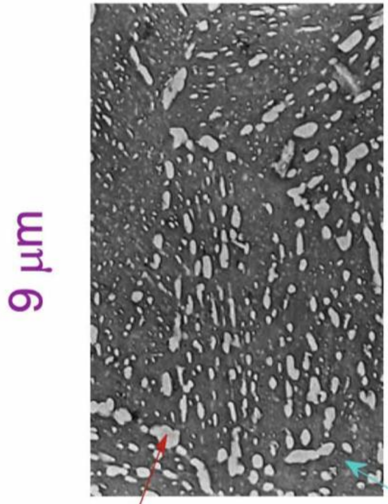
- Hardness: fine pearlite << martensite.

Tempered Martensite

Heat treat martensite to form tempered martensite

- tempered martensite less brittle than martensite
- tempering reduces internal stresses caused by quenching



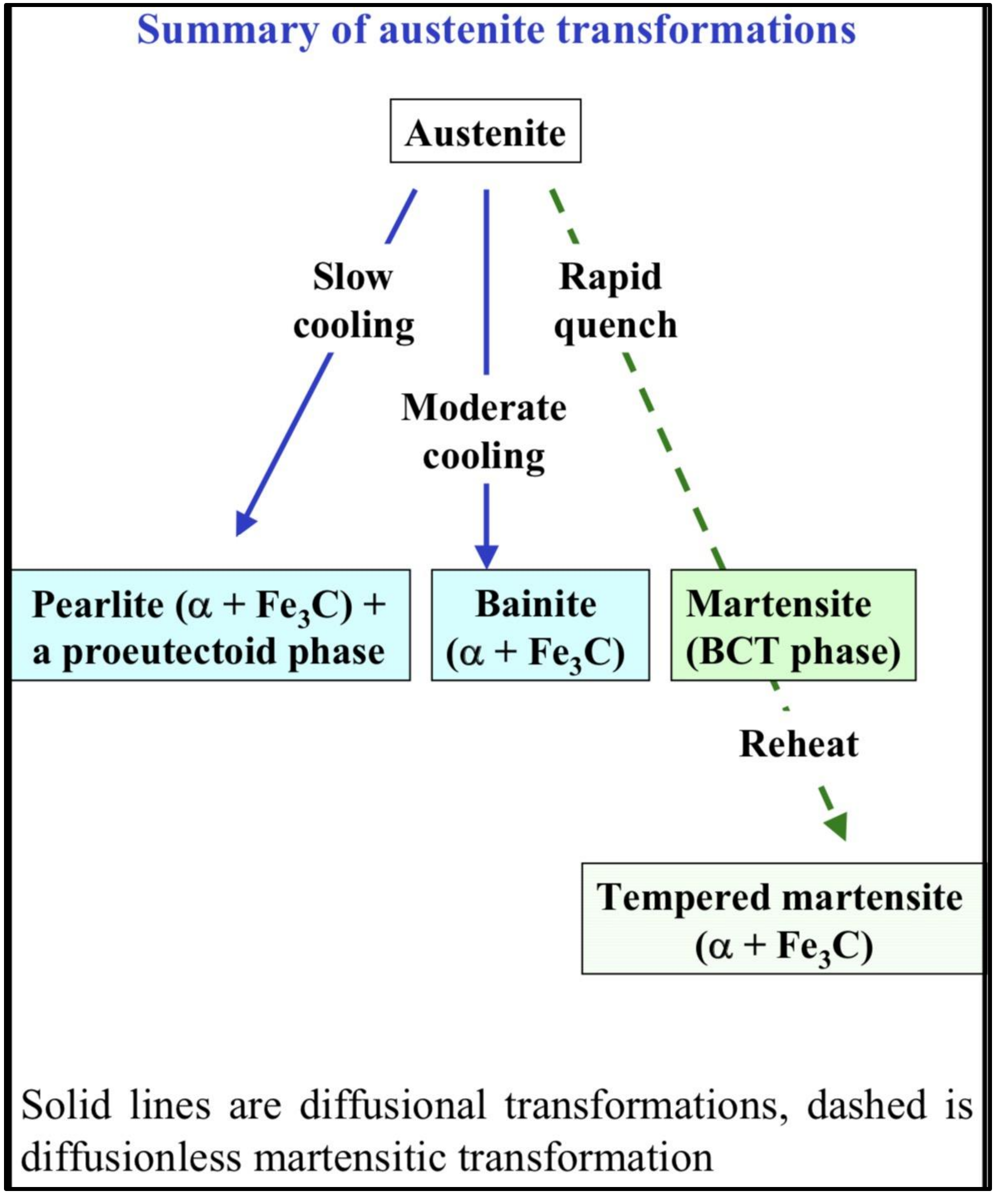


- tempering produces extremely small Fe_3C particles surrounded by α.
- tempering decreases *TS*, *YS* but increases %RA

As austenite cools, the resulting structure depends on cooling rate:

Slower gives pearlite, moderate gives bainite, and rapid quenching forms hard but brittle martensite.

Reheating martensite softens it into tempered martensite with better toughness.



Summary of austenite transformations

Austenite

Slow cooling → **Pearlite ($\alpha + Fe_3C$) + a proeutectoid phase**

Moderate cooling → **Bainite ($\alpha + Fe_3C$)**

Rapid quench → **Martensite (BCT phase)**

Reheat → **Tempered martensite ($\alpha + Fe_3C$)**

Solid lines are diffusional transformations, dashed is diffusionless martensitic transformation

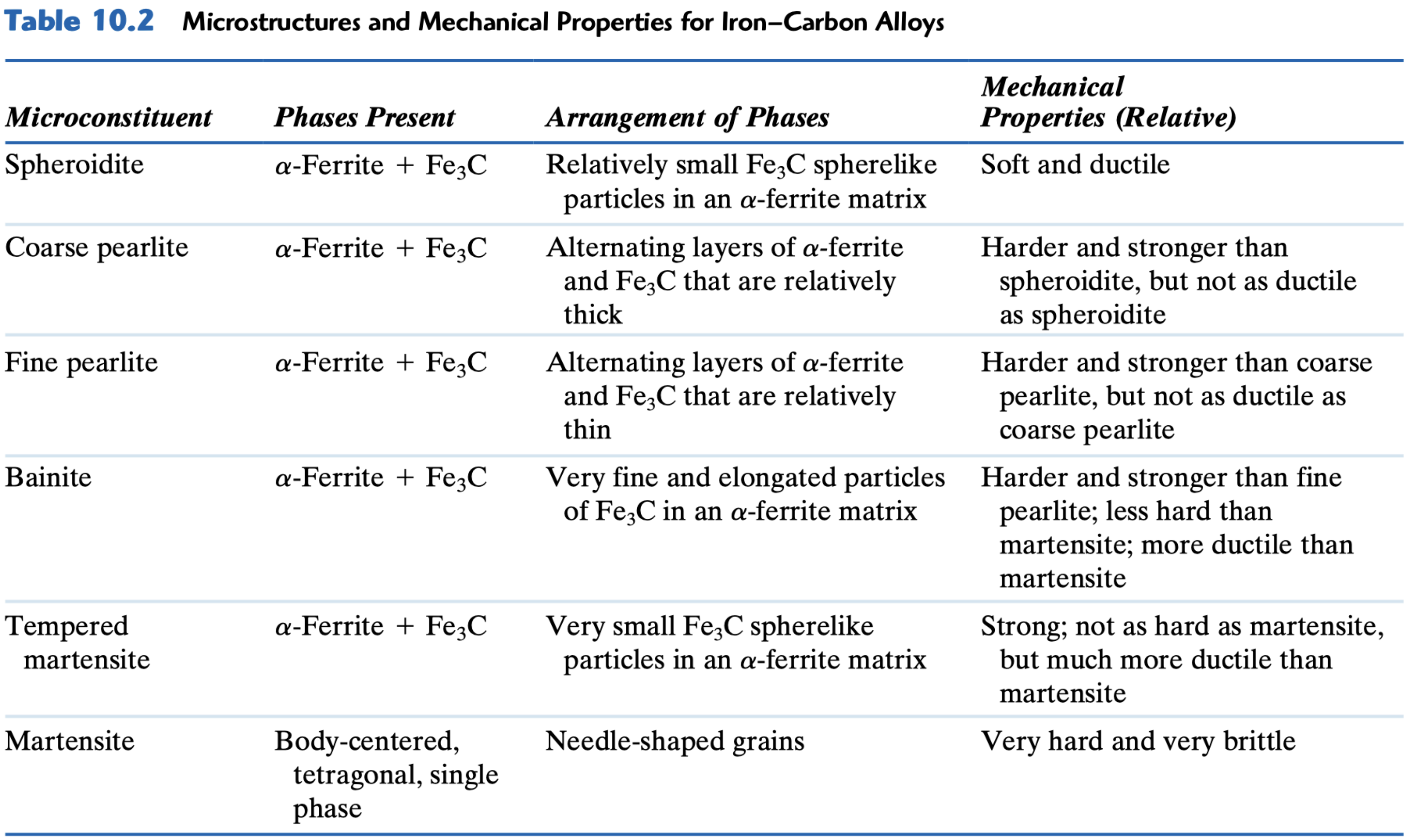


Table 10.2 Microstructures and Mechanical Properties for Iron–Carbon Alloys

Microconstituent	*Phases Present*	*Arrangement of Phases*	*Mechanical Properties (Relative)*
Spheroidite	α-Ferrite + Fe_3C	Relatively small Fe_3C spherelike particles in an α-ferrite matrix	Soft and ductile
Coarse pearlite	α-Ferrite + Fe_3C	Alternating layers of α-ferrite and Fe_3C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α-Ferrite + Fe_3C	Alternating layers of α-ferrite and Fe_3C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α-Ferrite + Fe_3C	Very fine and elongated particles of Fe_3C in an α-ferrite matrix	Harder and stronger than fine pearlite; less hard than martensite; more ductile than martensite
Tempered martensite	α-Ferrite + Fe_3C	Very small Fe_3C spherelike particles in an α-ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered, tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

EXAMPLE PROBLEM 10.4

Determination of Properties for a Eutectoid Fe–Fe_3C Alloy Subjected to an Isothermal Heat Treatment

Determine the tensile strength and ductility (%RA) of a eutectoid Fe–Fe_3C alloy that has been subjected to heat treatment (c) in Example Problem 10.3.

(c) Rapidly cool to **650°C**, hold for **20 s**, rapidly cool to **400°C**, hold for **10^3 s**, and quench to room temperature.

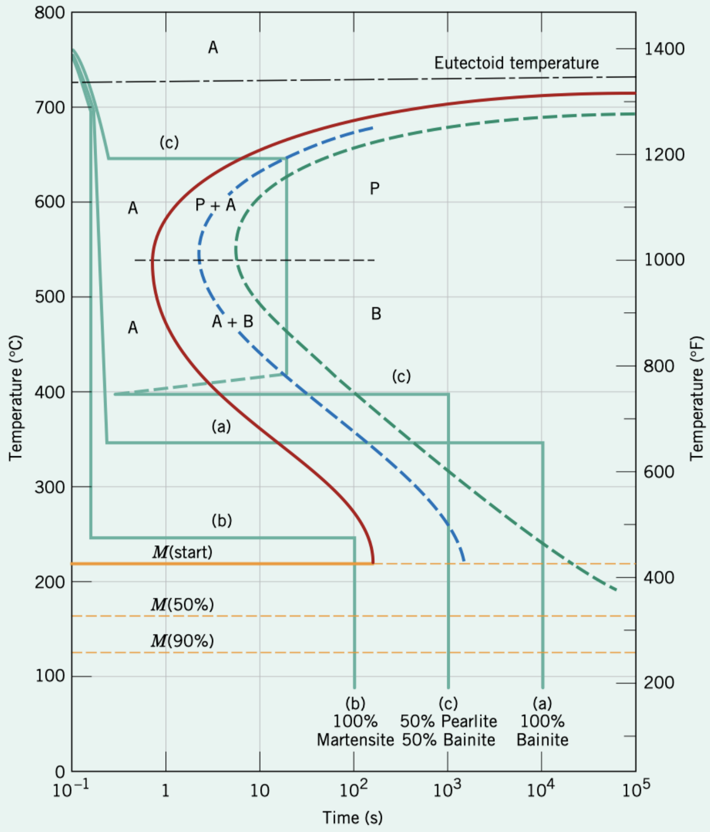
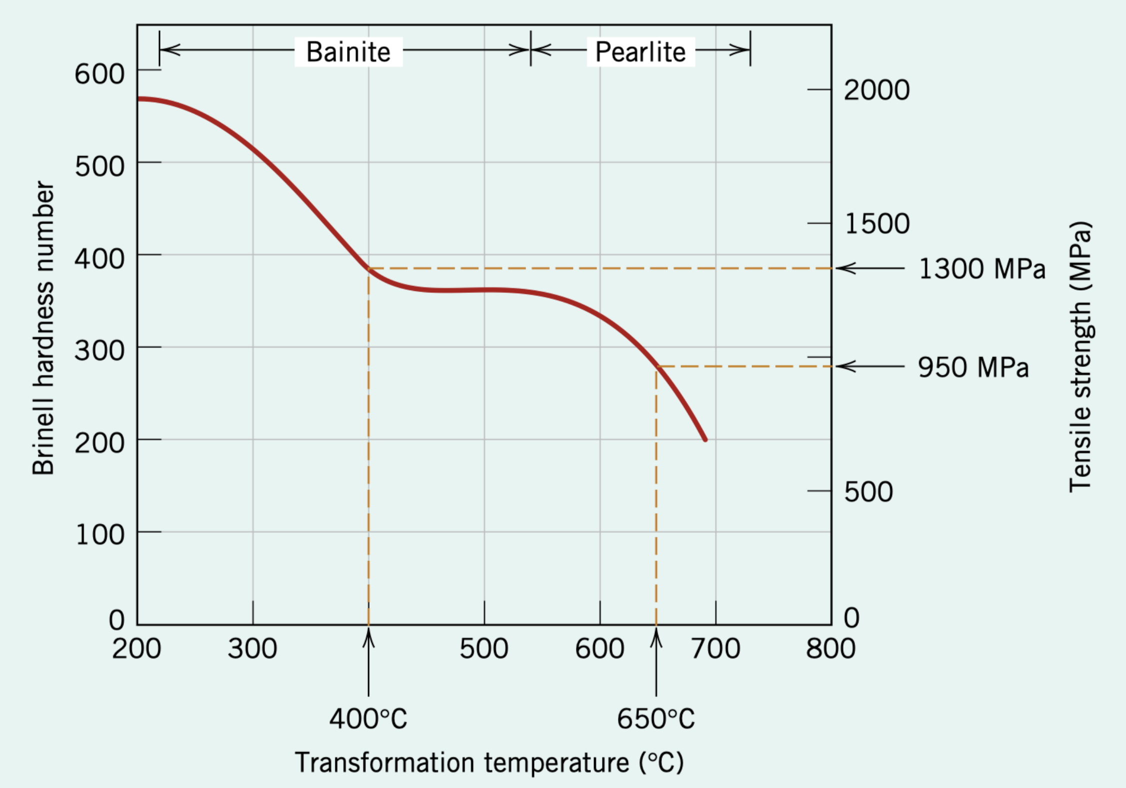


Figure 10.24 Isothermal transformation diagram for an iron–carbon alloy of eutectoid composition and the isothermal heat treatments (a), (b), and (c) in Example Problem 10.3.

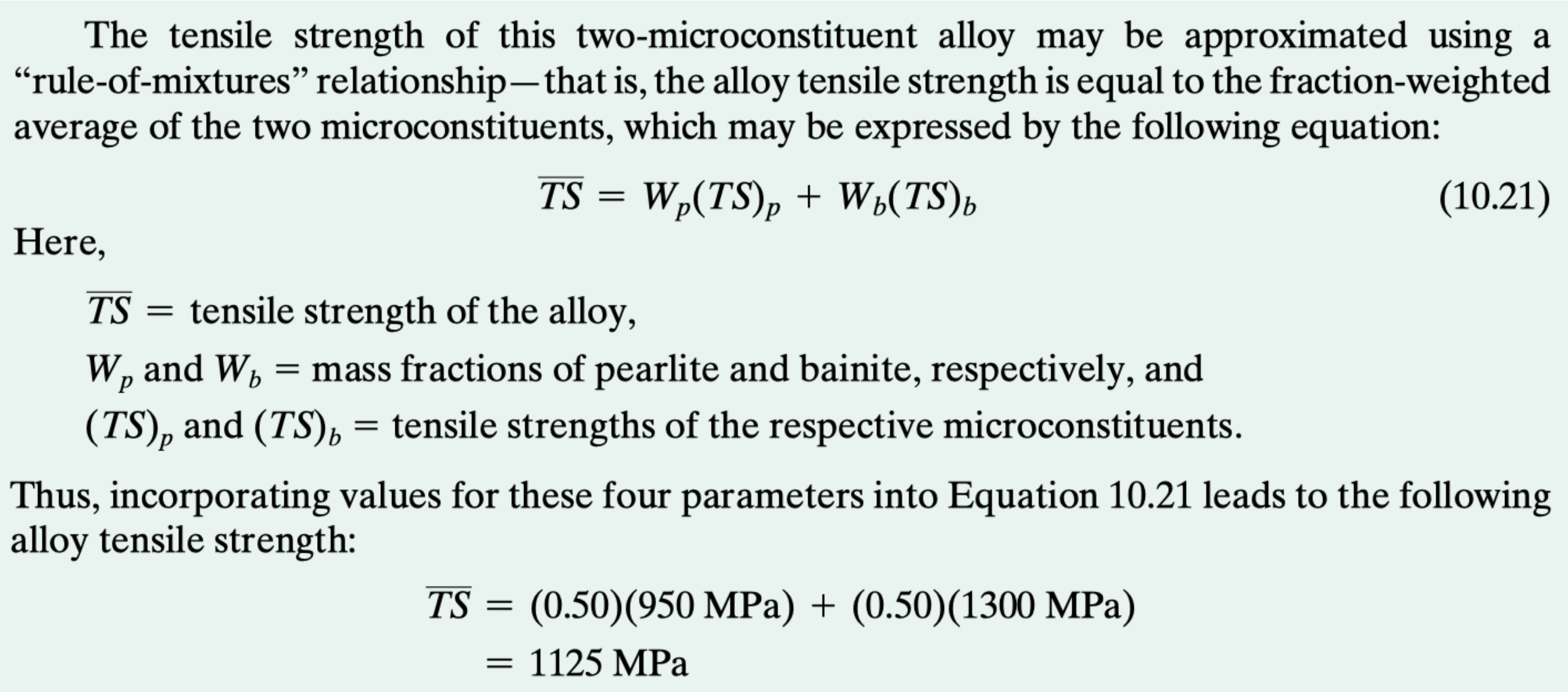
[Example adopted from Callister 9e, page 392]

Solution

According to Figure 10.24, the final microstructure for heat treatment (c) consists of approximately 50% pearlite that formed during the 650°C isothermal heat treatment, whereas the remaining 50% austenite transformed to bainite at 400°C; thus, the final microstructure is 50% pearlite and 50% bainite. The tensile strength may be determined using Figure 10.31*a*. For pearlite, which was formed at an isothermal transformation temperature of 650°C, the tensile strength is approximately 950 MPa, whereas using this same plot, the bainite that formed at 400°C has an approximate tensile strength of 1300 MPa. Determination of these two tensile strength values is demonstrated in the following illustration.



Solution continue ..



The tensile strength of this two-microconstituent alloy may be approximated using a "rule-of-mixtures" relationship—that is, the alloy tensile strength is equal to the fraction-weighted average of the two microconstituents, which may be expressed by the following equation:

$$\overline{TS} = W_p(TS)_p + W_b(TS)_b \tag{10.21}$$

Here,

$\overline{TS}$ = tensile strength of the alloy,

W_p and W_b = mass fractions of pearlite and bainite, respectively, and

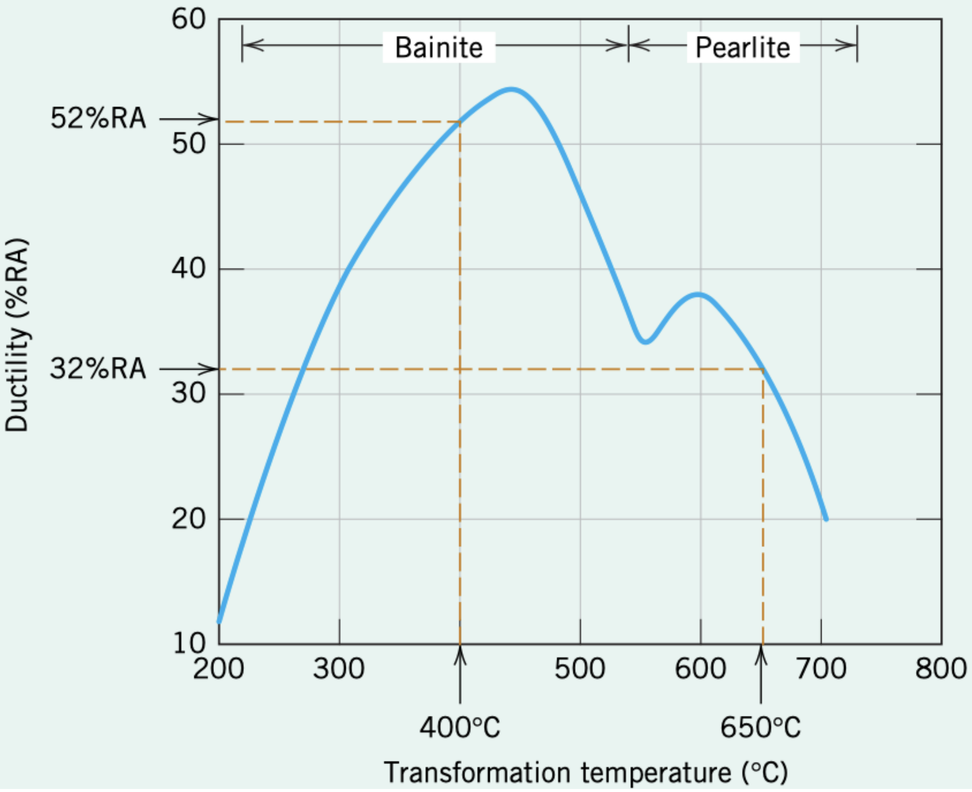
$(TS)_p$ and $(TS)_b$ = tensile strengths of the respective microconstituents.

Thus, incorporating values for these four parameters into Equation 10.21 leads to the following alloy tensile strength:

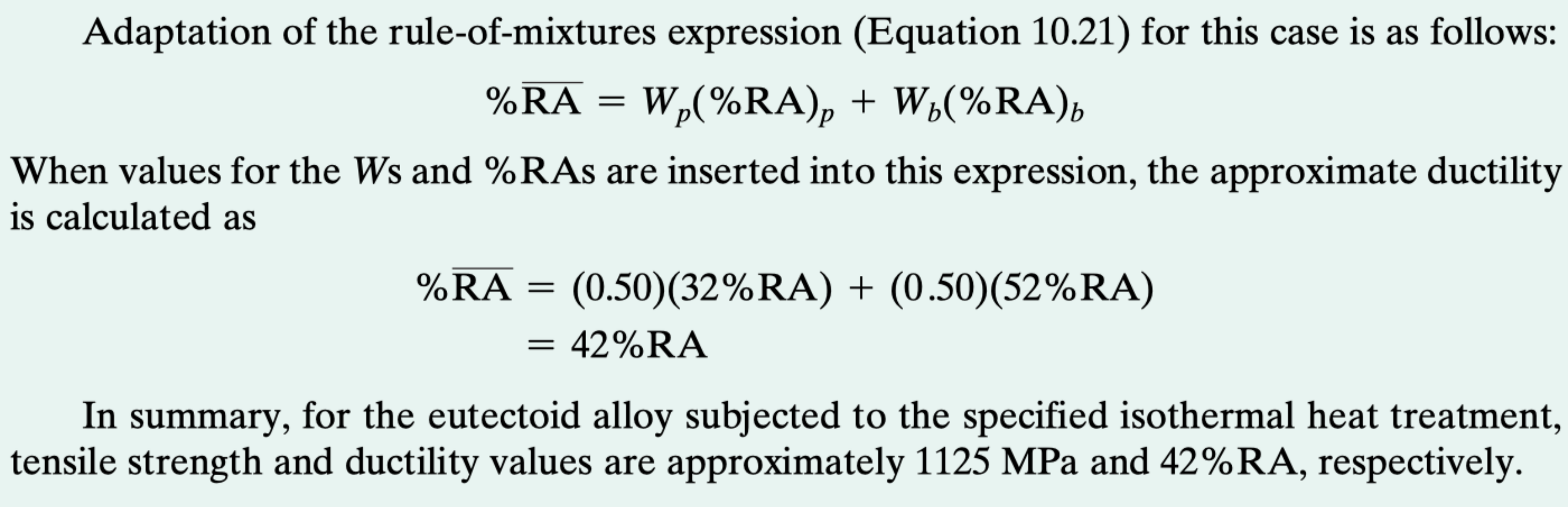
$$\begin{aligned}\overline{TS} &= (0.50)(950\text{ MPa}) + (0.50)(1300\text{ MPa}) \\ &= 1125\text{ MPa}\end{aligned}$$

Solution continue ..

This same technique is used for the computation of ductility. In this case, approximate ductility values for the two microconstituents, taken at 650°C (for pearlite) and 400°C (for bainite), are, respectively, 32%RA and 52%RA, as taken from the following adaptation of Figure 10.31*b*:



Solution continue ..



Adaptation of the rule-of-mixtures expression (Equation 10.21) for this case is as follows:

$$\%\overline{\mathrm{RA}} = W_p(\%\mathrm{RA})_p + W_b(\%\mathrm{RA})_b$$

When values for the *W*s and %RAs are inserted into this expression, the approximate ductility is calculated as

$$\begin{aligned}\%\overline{\mathrm{RA}} &= (0.50)(32\%\mathrm{RA}) + (0.50)(52\%\mathrm{RA}) \\ &= 42\%\mathrm{RA}\end{aligned}$$

In summary, for the eutectoid alloy subjected to the specified isothermal heat treatment, tensile strength and ductility values are approximately 1125 MPa and 42%RA, respectively.

🔍 Case Studies: Real-World Applications of Phase Transformations

⚙️ 1. Gear Teeth Hardening (Martensitic Transformation)

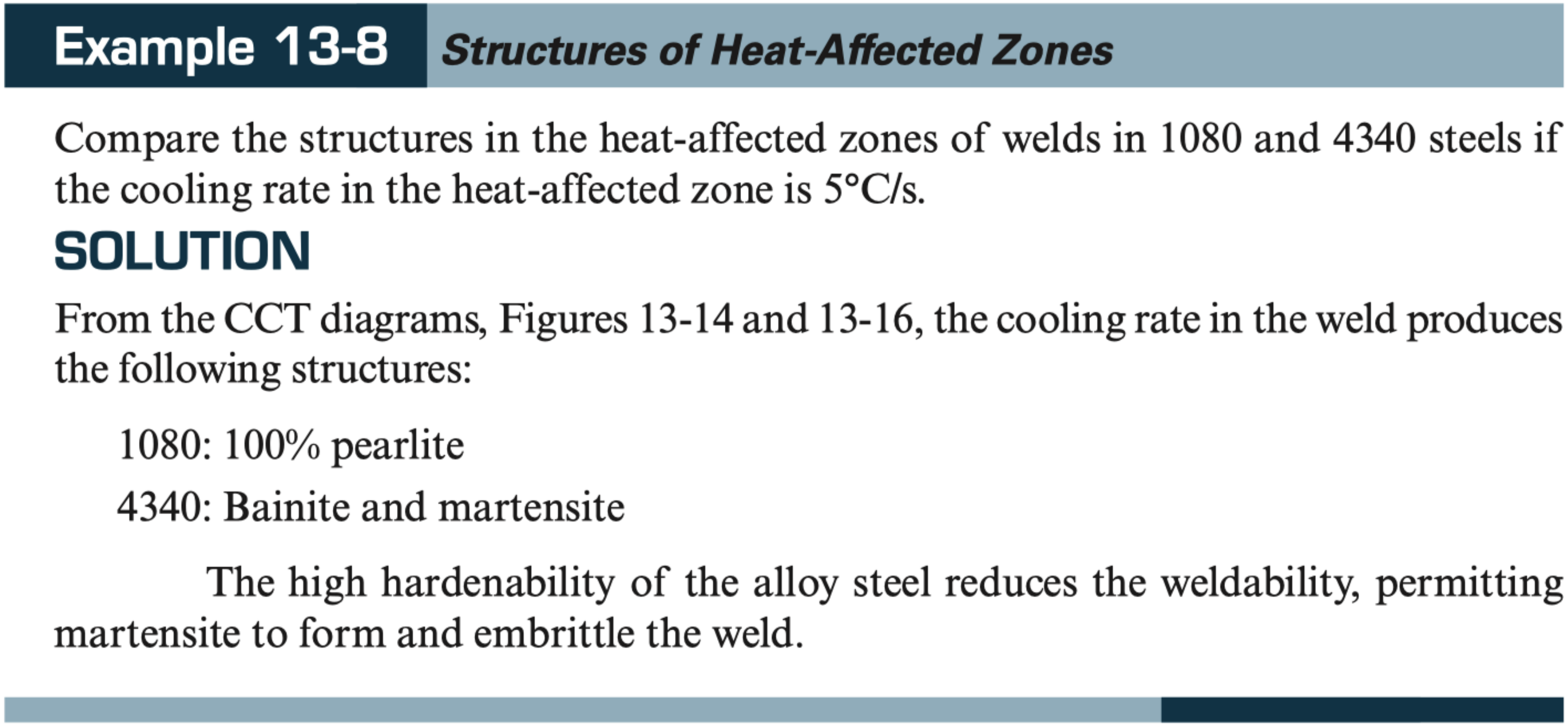
- Gear surfaces are **rapidly quenched** to form **martensite**.
- Increases **hardness and wear resistance**, while the core remains tough.

🚗 2. Dual-Phase Steels in Automotive Industry

- Steels contain **ferrite (soft)** + **martensite (hard)**.
- Offer an excellent **strength-ductility balance**.
- Widely used in **car bodies and safety components**.

🔧 3. TTT Diagrams in Welding

- Used to **predict phase changes** during cooling.
- Helps in designing **controlled cooling schedules** to avoid **brittle phases** (e.g., martensite in HAZ).
- Ensures **structural integrity** in welded joints.



Example 13-8 *Structures of Heat-Affected Zones*

Compare the structures in the heat-affected zones of welds in 1080 and 4340 steels if the cooling rate in the heat-affected zone is 5°C/s.

SOLUTION

From the CCT diagrams, Figures 13-14 and 13-16, the cooling rate in the weld produces the following structures:

1080: 100% pearlite

4340: Bainite and martensite

The high hardenability of the alloy steel reduces the weldability, permitting martensite to form and embrittle the weld.

[Example adopted from Askeland 7e, page 485]

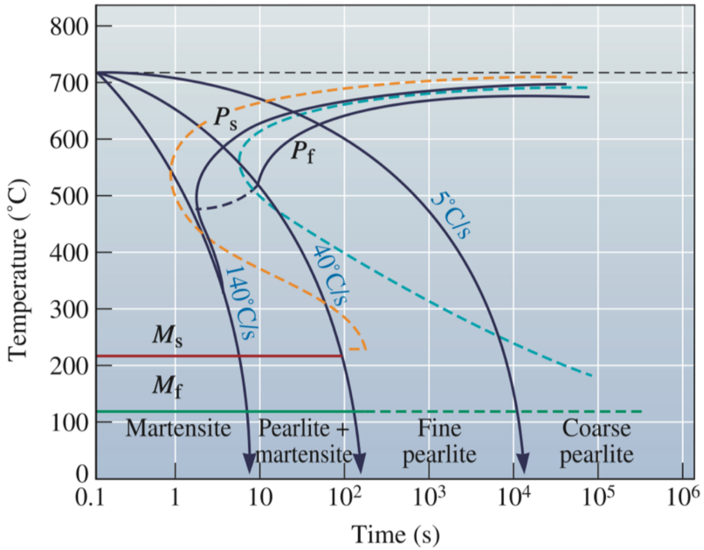


Figure 13-14 The CCT diagram (solid lines) for a 1080 steel compared with the TTT diagram (dashed lines).

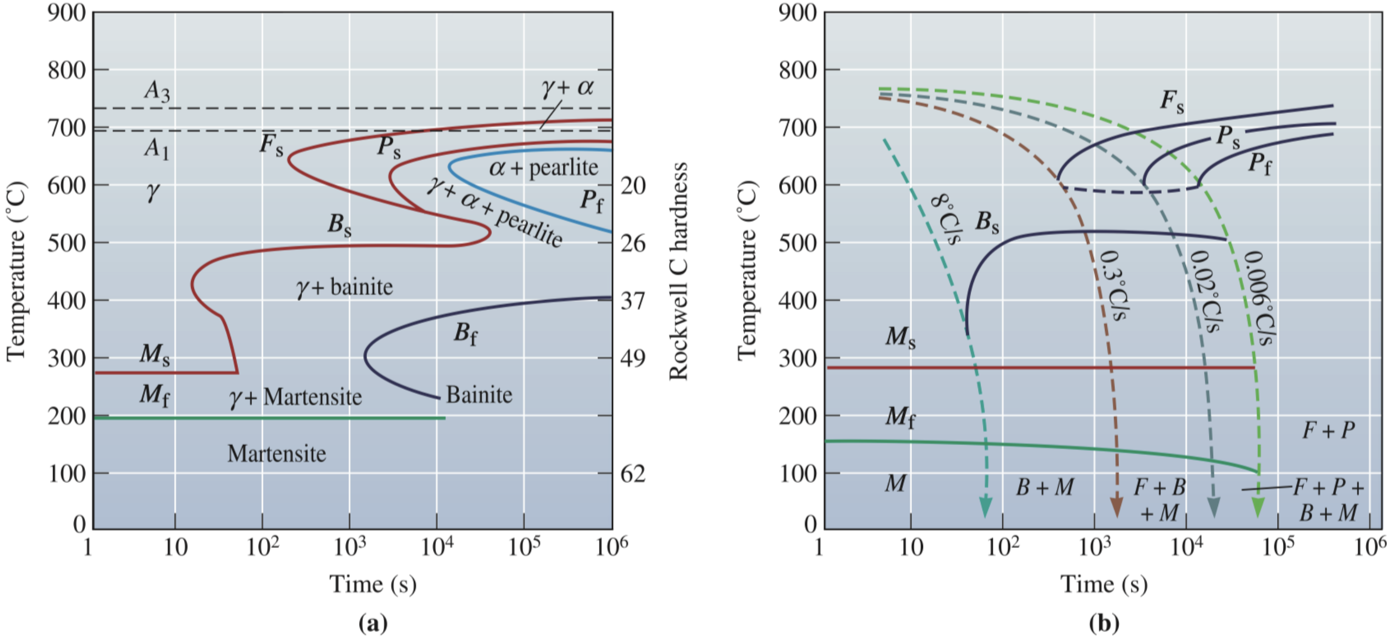


Figure 13-16 (a) TTT and (b) CCT diagrams for a 4340 steel.