Metallic Materials

Phase Transformations in Metals

Why Study Phase Transformations in Metals?

- **The development of a set of desirable mechanical properties for a material often results from a phase transformation, which is wrought by a heat treatment.**

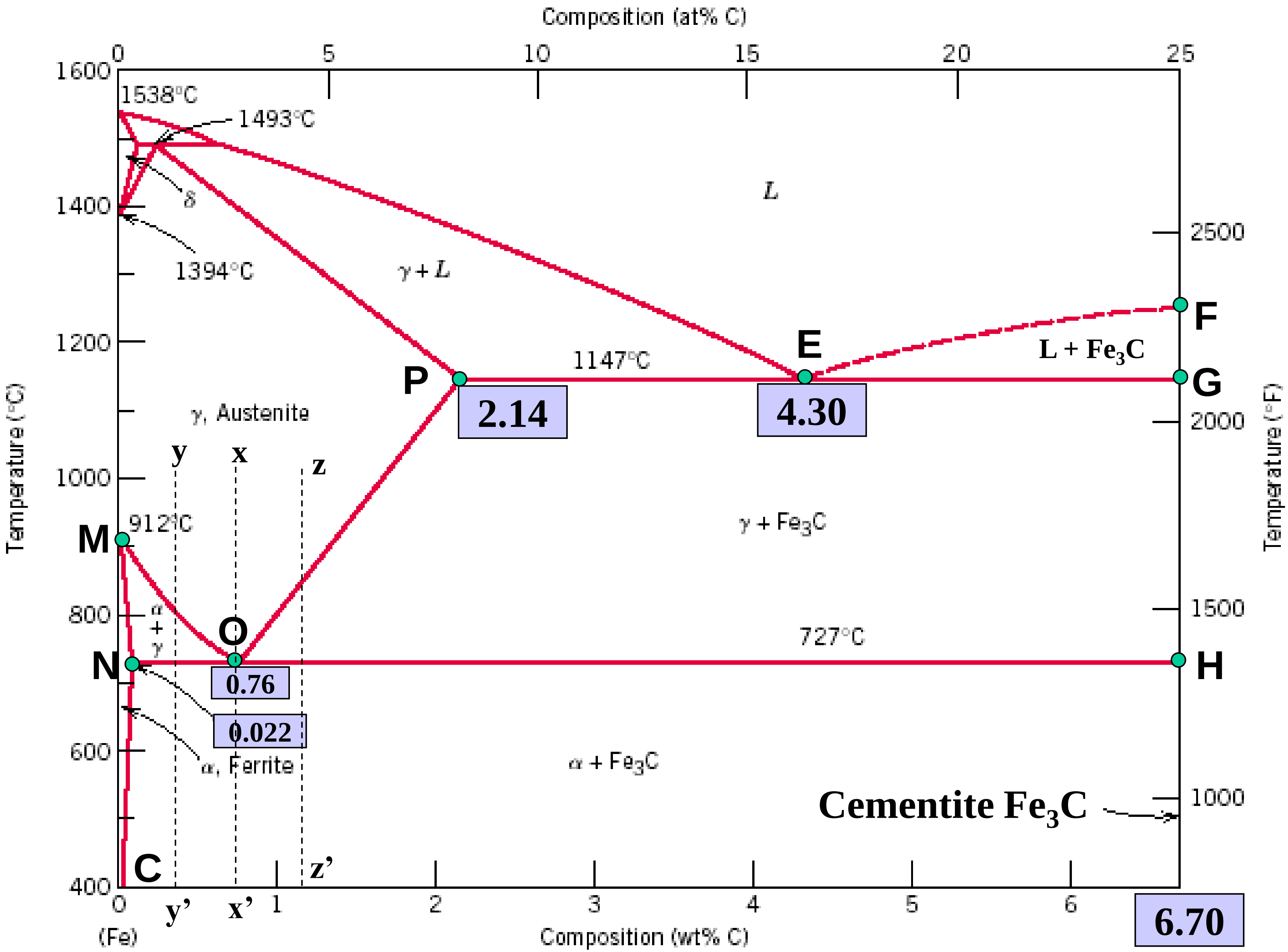
- **The time and temperature dependencies of some phase transformations are conveniently represented on modified phase diagrams.**

  It is important to know how to use these diagrams in order to design a heat treatment for some alloy that will yield the desired room-temperature mechanical properties.

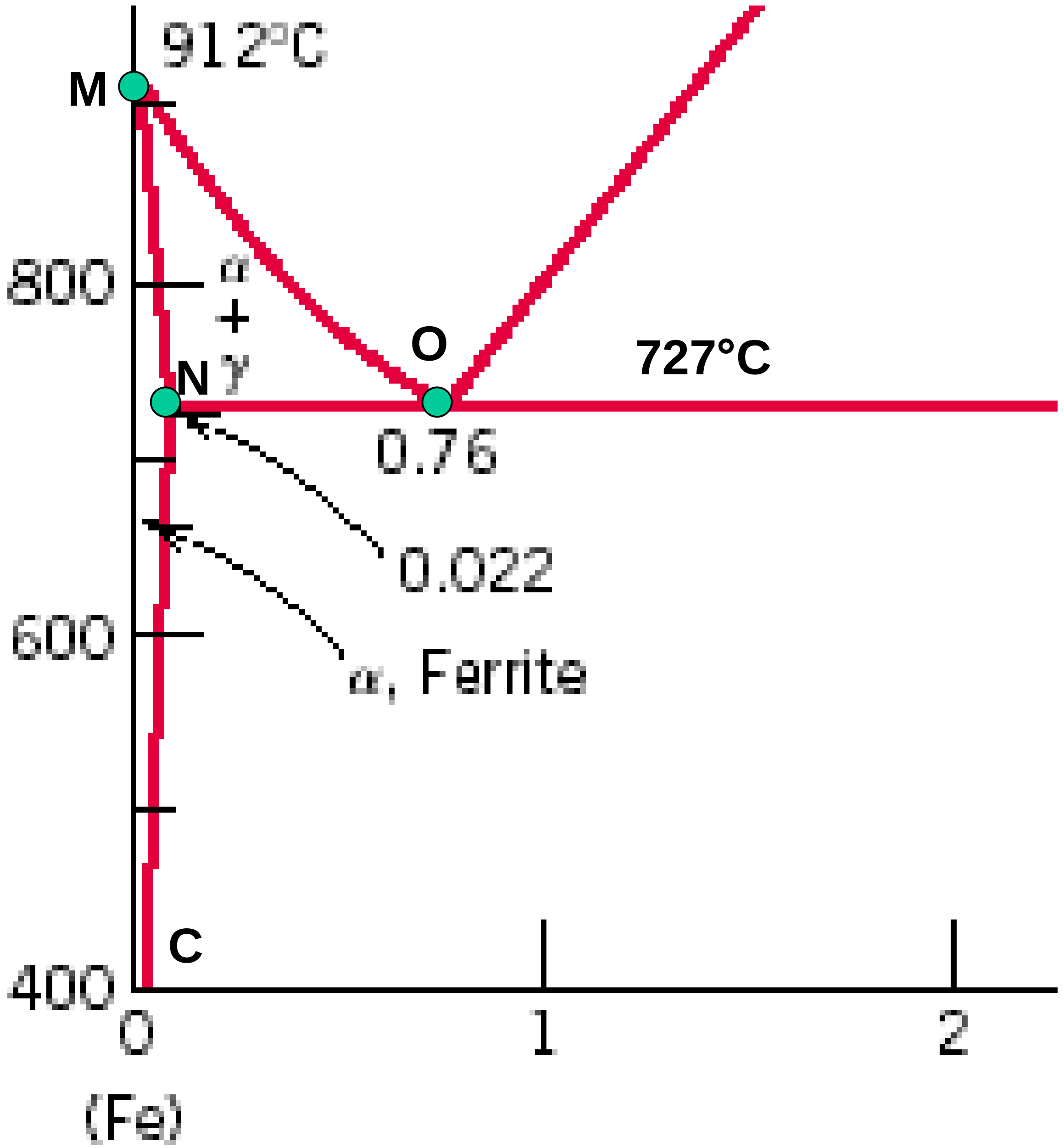
- **The tensile strength of an iron-carbon alloy of eutectoid composition (0.76wt% C) can be varied between ~ 700 MPa and 2000 MPa depending on the heat treatment employed.**

How to tailor mechanical properties of metallic materials?

- **Four strengthening mechanisms:**
  - **Grain size refinement**
  - **Solid-solution strengthening**
  - **Strain hardening**
  - **Precipitation hardening**
- **Additional techniques are available wherein the mechanical properties are reliant on the characteristics of the microstructure.**
- **The development of microstructure in both single- and two-phase alloys ordinarily involves some type of phase transformation — an alteration in the number and/or character of the phases.**



The iron–iron carbide phase diagram



The iron–iron carbide phase diagram

Important Phases in the Iron-Iron Carbide System

- **Thermal processing or heat treating: the art and science of controlling thermal energy for the purpose of altering the properties of metals and alloys**
  - **Ferrite (α-Fe): Pure Fe (room temperature to 912°C), a single-phase BCC solid solution**

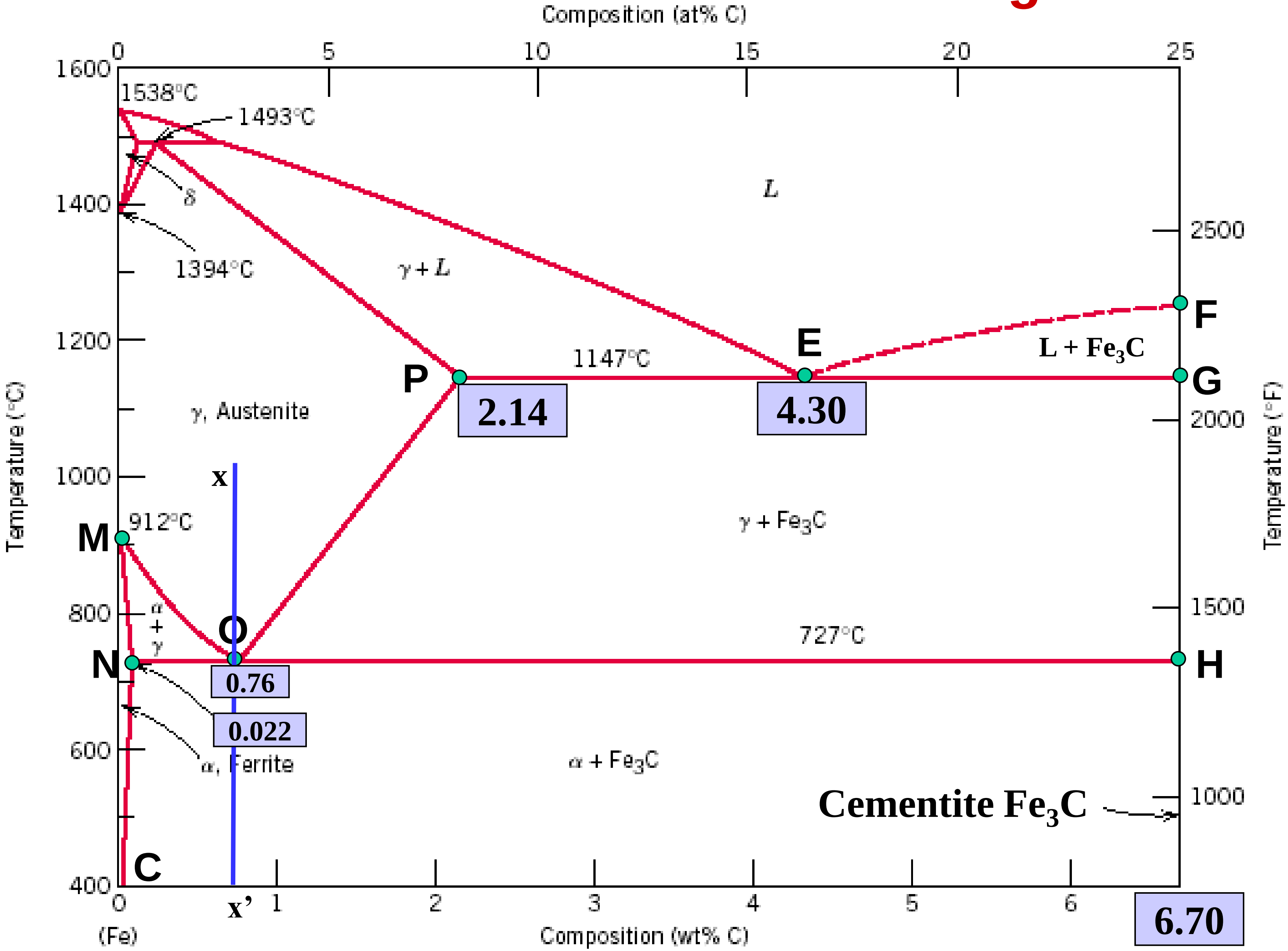
    Ferrite can accommodate 0.022% carbon at 727°C.
  - **Austenite (γ-Fe): a single-phase FCC solid solution**

    α ferrite transforms from BCC to FCC at 912°C.

    Characteristics: ability to be deformed and to absorb carbon up to 2.14% at 1147°C
  - **Cementite (iron carbide Fe_3C): intermediate phase with the chemical formula Fe_3C**

    6.70% C: brittle and hard

The Iron–Iron Carbide Phase Diagram.



Important Phases in the Iron-Iron Carbide System (Cont'd)

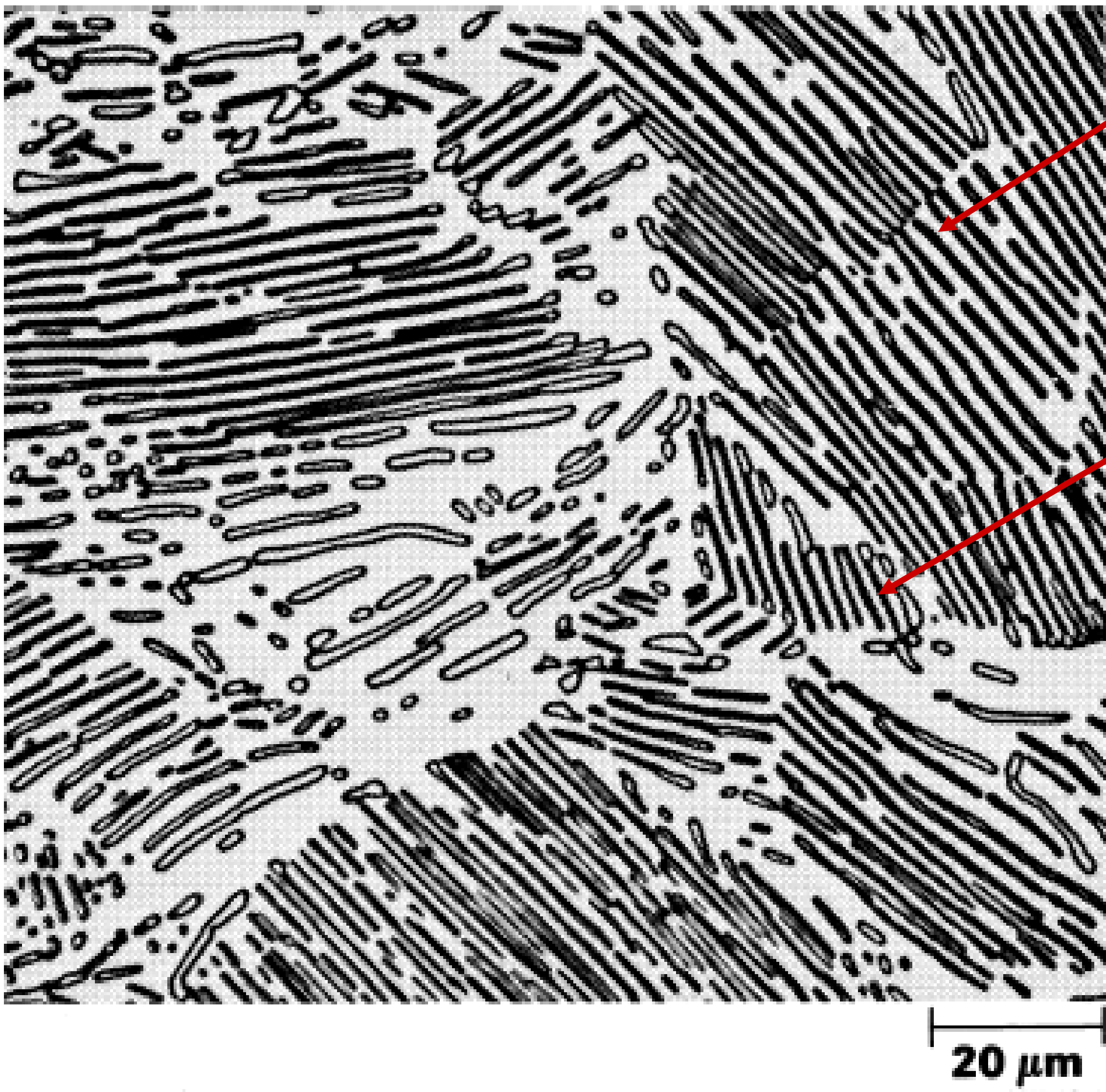
– Pearlite:

  When steel with the eutectoid composition forms at 727°C, it produces a lamellar two-phase mixture of ferrite and cementite

– Hypoeutectoid steel: a mixture of ferrite and pearlite

– Hypereutectoid steel: a mixture of pearlite and cementite

Pearlite Microstructure



Pearlite has mechanical properties between the soft, ductile ferrite and the hard, brittle cementite.

Photomicrograph of a eutectoid steel showing the pearlite microstructure consisting of alternating layers of α ferrite (the light phase) and Fe_3C (thin layers most of which appear dark). 500X.

The Iron-Iron Carbide System

- One eutectic reaction exists for the iron-iron carbide system, at 4.30wt% C and 1147°C (Line PEG).

  $L\ (4.30\text{wt\% C}) \rightarrow \gamma\ (2.14\text{wt\% C}) + Fe_3C\ (6.70\text{wt\% C})$

- One eutectoid reaction exists for the iron-iron carbide system, at 0.76wt% C and 727°C (Line NOH).

  $\gamma\ (0.76\text{wt\% C}) \rightarrow \alpha\ (0.022\text{wt\% C}) + Fe_3C\ (6.70\text{wt\% C})$

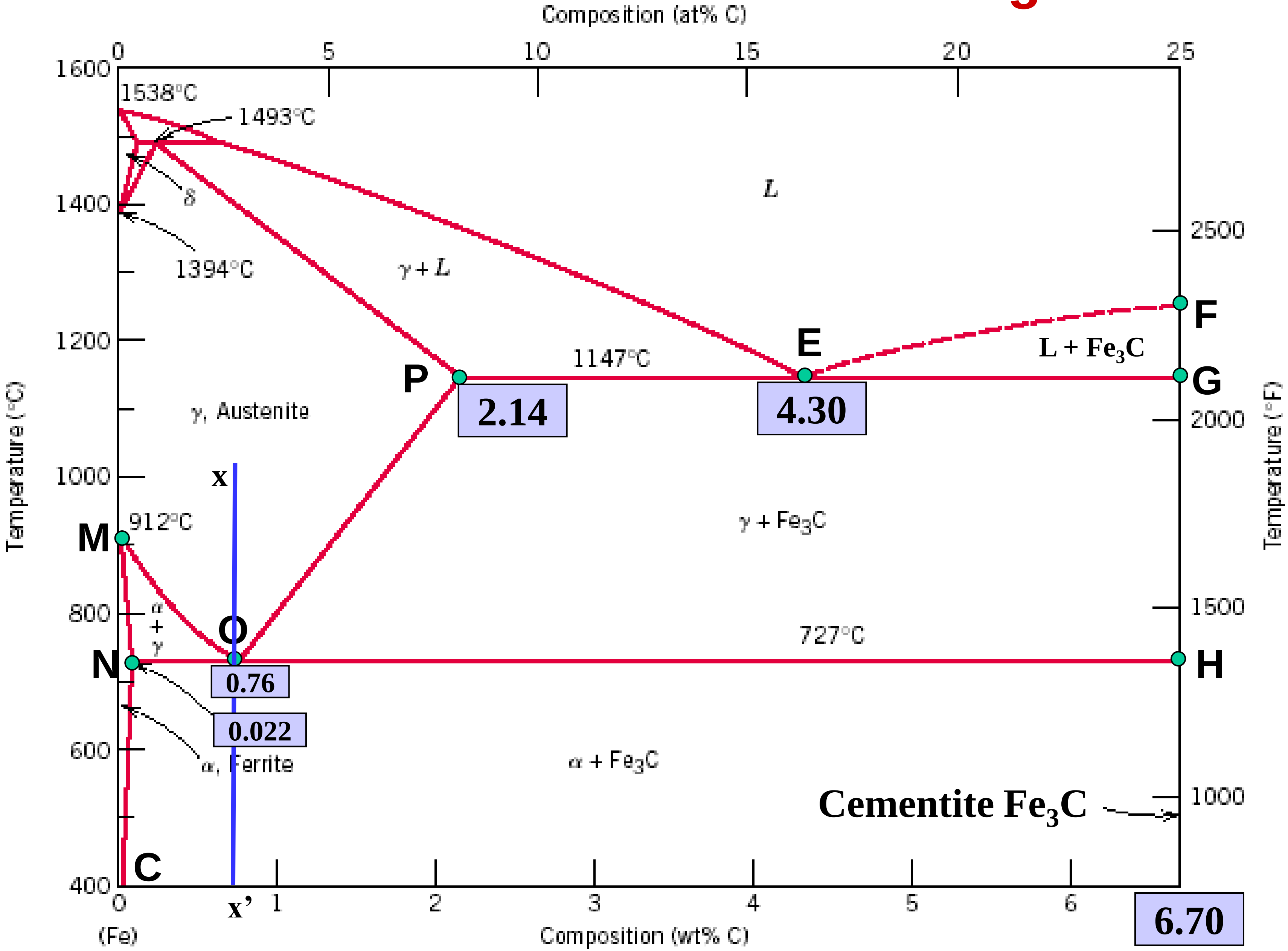
Phase Transformations

- Phase Transformation: **a change in the number and/or character of the phases that constitute the microstructure of an alloy**
- **In general, two processes accompany the phase transformation such as the eutectoid reaction:**
  - Nucleation — **the formation of very small particles, or nuclei, of the new phase**

    Favorable nucleation sites: imperfection sites, especially grain boundaries
  - Growth — **the increase of the nuclei in size**

    Some volume of the parent phase disappears.

The Iron–Iron Carbide Phase Diagram.



The Limitation of Equilibrium Phase Diagrams

- **Unable to indicate the time period required for the attainment of equilibrium**
- **Equilibrium conditions are maintained only if heating or cooling is carried out at <u>extremely slow</u> and unpractical rates.**

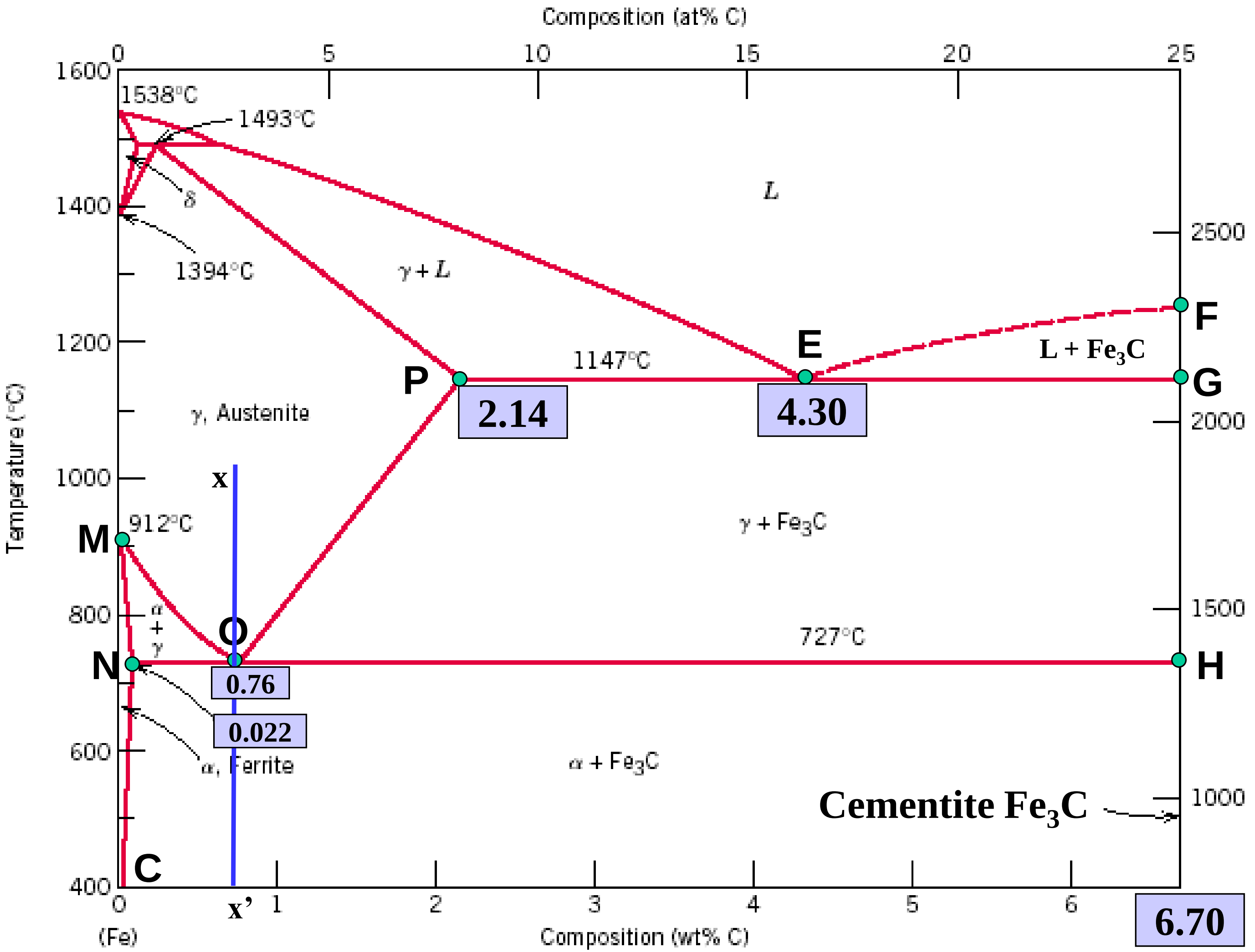
Time-Temperature-Transformation (T-T-T) Diagrams

Pearlite

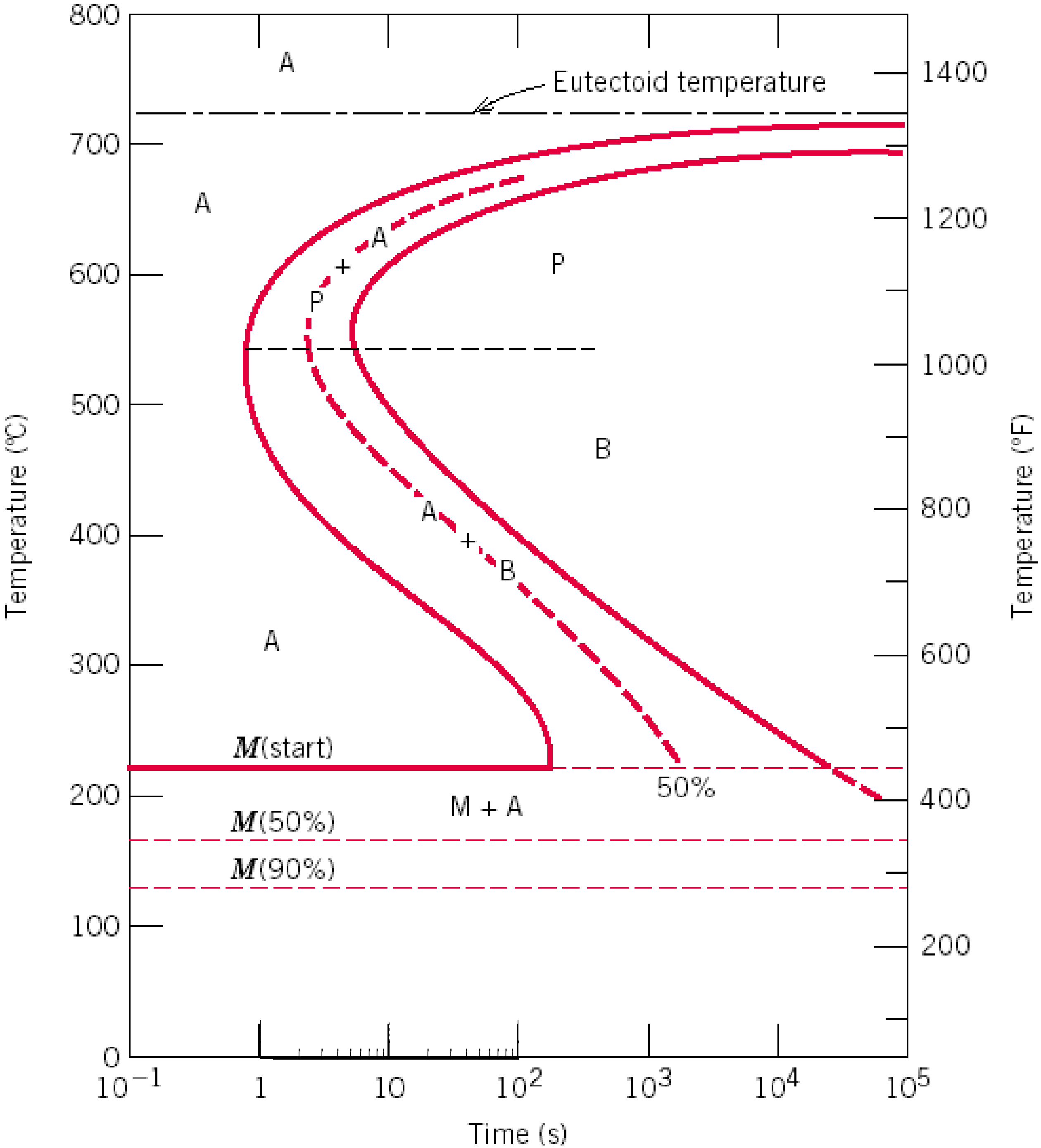
- **The eutectoid reaction is fundamental to the development of microstructures in steel alloys.**

  γ **(0.76 wt% C)** $\rightleftharpoons$ α **(0.022 wt% C) + Fe_3C (6.70 wt% C)**

- **Pearlite is the microstructural product of this transformation.**
- **Interpretation of the TTT diagram**
  - **Above eutectoid temperature: only <u>austenite</u> exists**
  - **Below eutectoid temperature: <u>nucleation</u> + <u>growth</u>**
- **The percentage of the transformation product is related to the holding <u>temperature</u> and holding <u>time</u>.**



The iron–iron carbide phase diagram



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

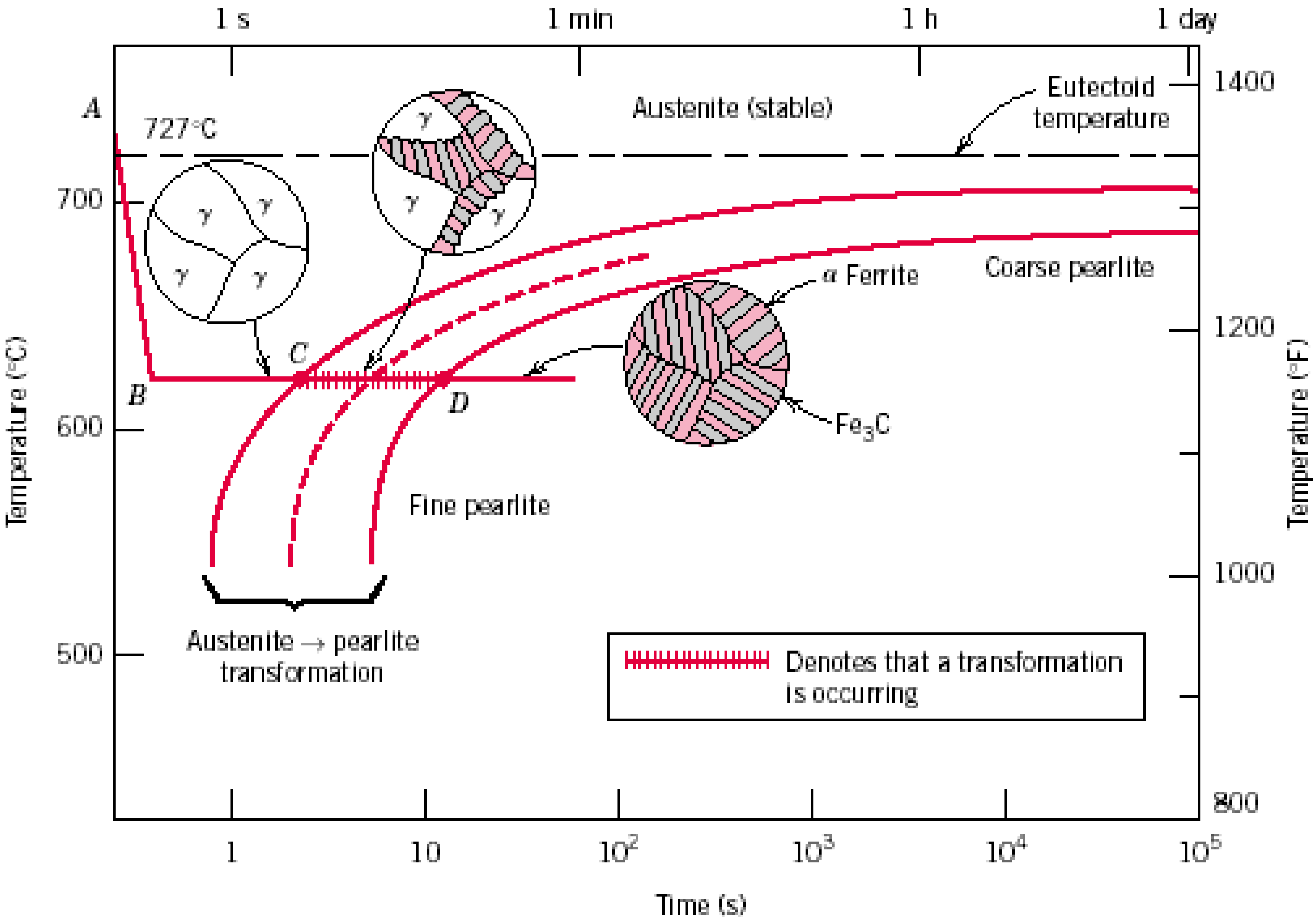
A: austenite

B: bainite

M: martensite

P: pearlite

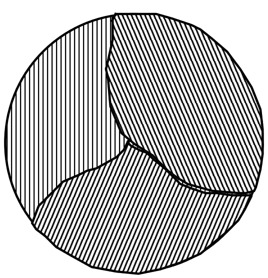
TTT Diagram for a Eutectoid Fe-C Alloy



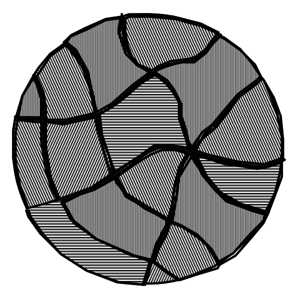
Time-Temperature-Transformation (T-T-T) Diagrams

Pearlite

- **The thickness of the ferrite/cementite layers in pearlite depends on the temperature. With decreasing temperature, the layers become progressively thinner.**
  - **At temperatures just below eutectoid → relatively thick layers → coarse pearlite**
  - **In the vicinity of 540°C → relatively thin layers → fine pearlite**



- Smaller ΔT: colonies are larger

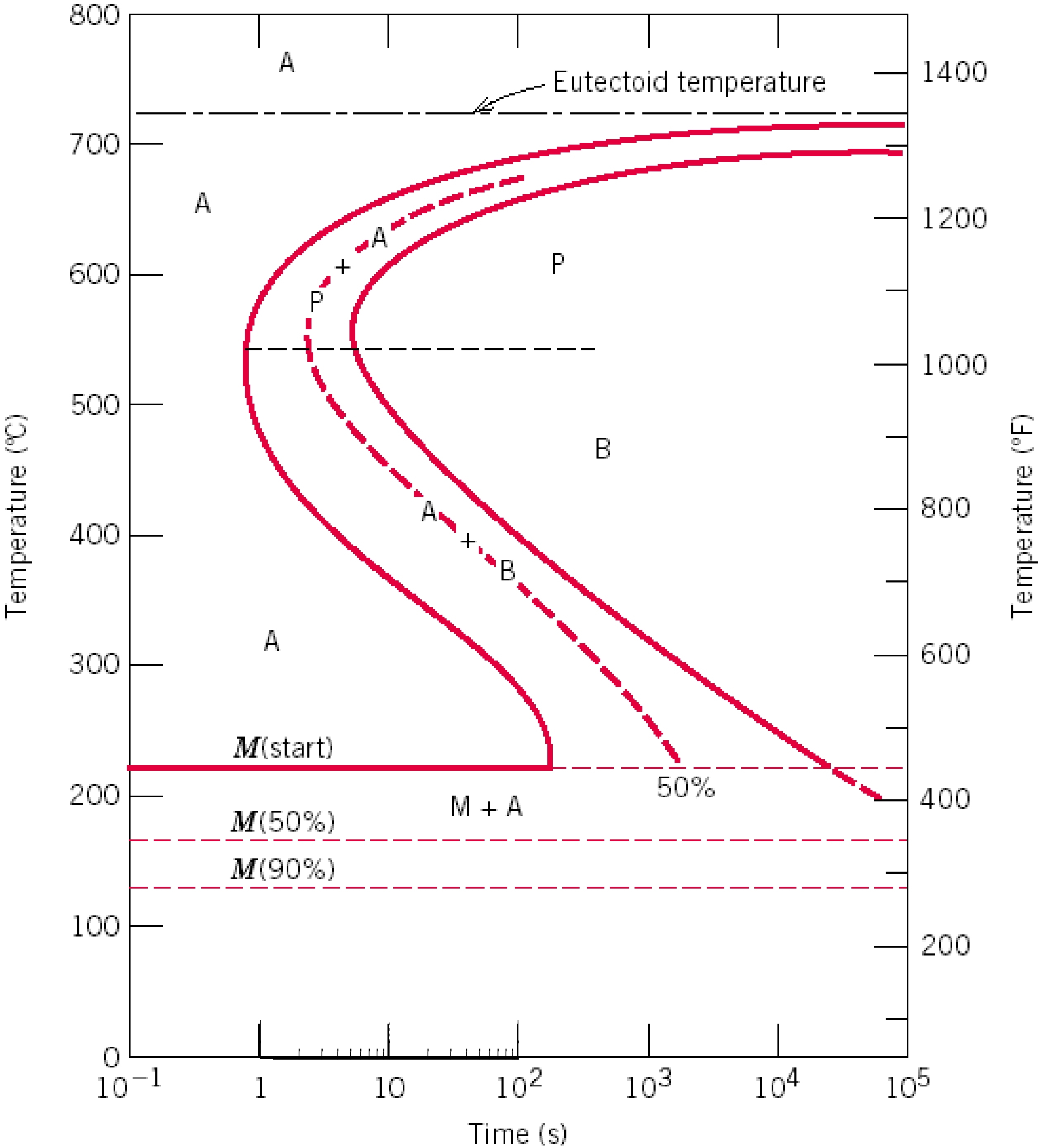


- Larger ΔT: colonies are smaller

(a) Coarse Pearlite

(b) Fine Pearlite

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



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

A: austenite

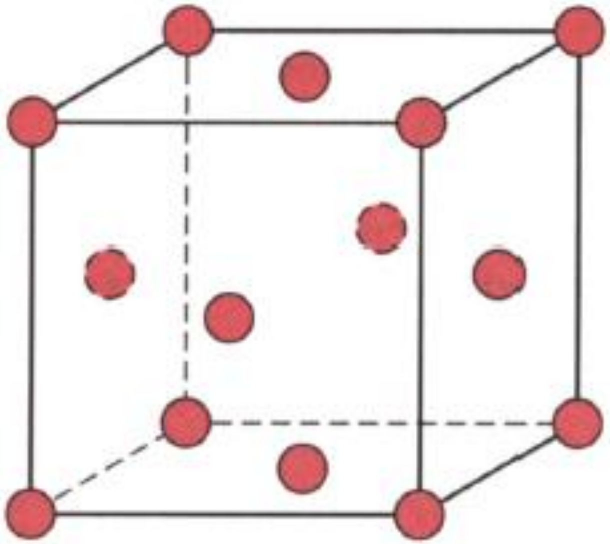
B: bainite

M: martensite

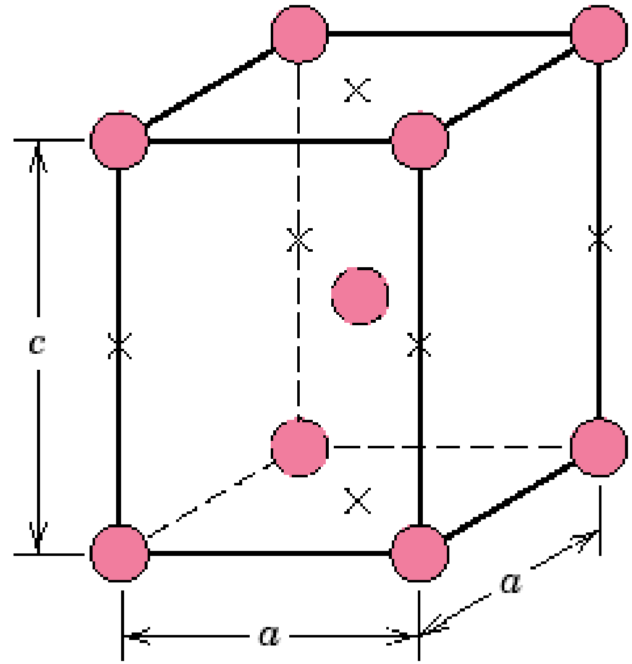
P: pearlite

Martensite

- **Martensite is formed when austenitized Fe-C alloys are rapidly cooled (or quenched) to a relatively low temperature (in the vicinity of the ambient).**
  - **Non-equilibrium single phase**
  - **A transformation product that is competitive with pearlite**
  - **Transformation of FCC to BCT (body-centered tetragonal)**
  - **Occurs instantaneously → time-independent**
  - **The martensite grains nucleate and grow at a very rapid rate — the velocity of sound within the austenite matrix.**



FCC Austenite
(γ phase)

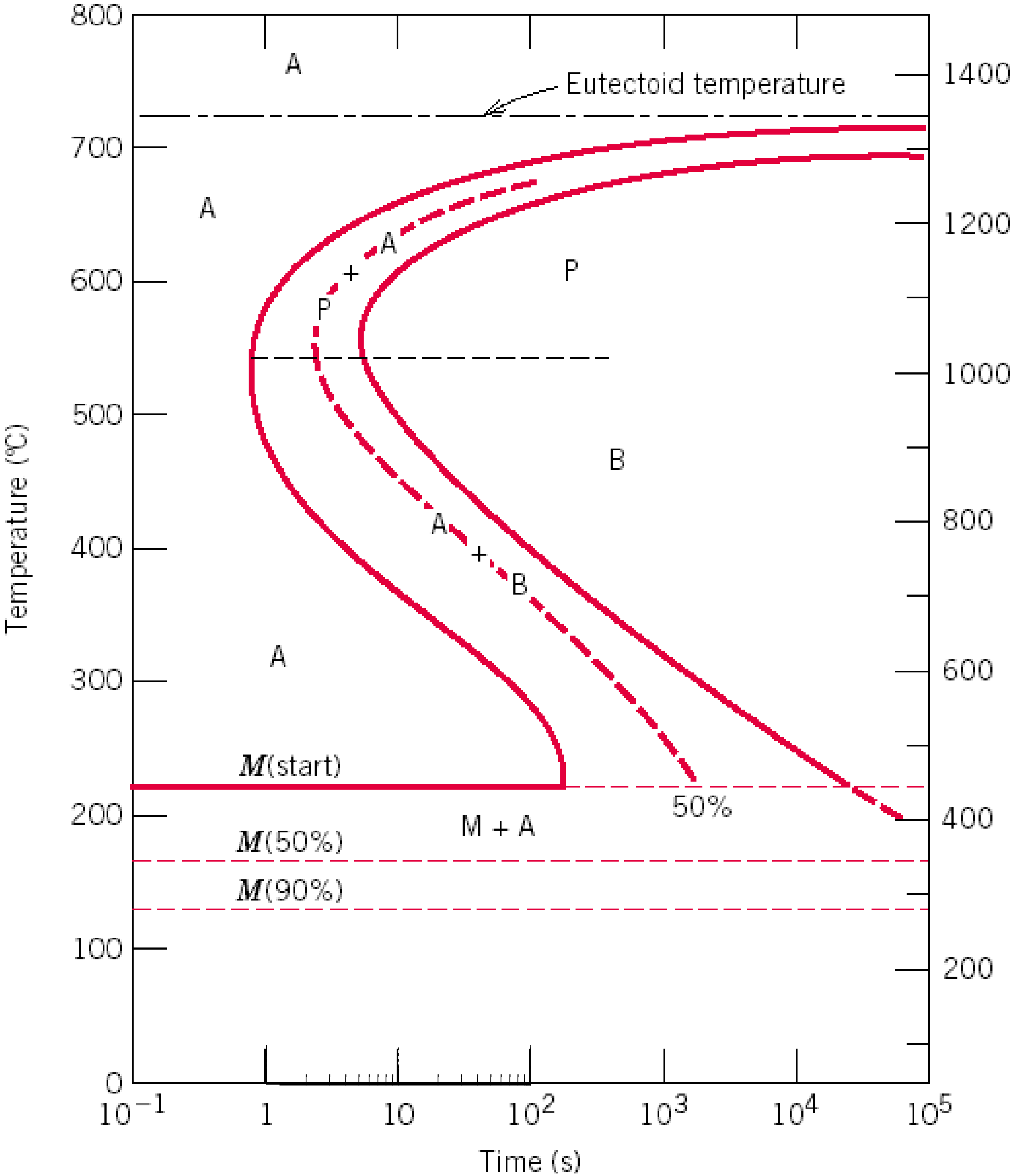


BCT Martensite
(body-centered tetragonal)

The body-centered tetragonal unit cell for martensitic steel showing iron atoms (circles) and sites that may be occupied by carbon atoms (crosses). For this tetragonal unit cell, c > a.

Lenticular or plate martensitic microstructure

Photomicrograph showing the lenticular or plate martensitic microstructure. The needle-shaped grains are the martensite phase, and the white regions are austenite that failed to transform during the rapid quench. 1220X.



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

A: austenite

B: bainite

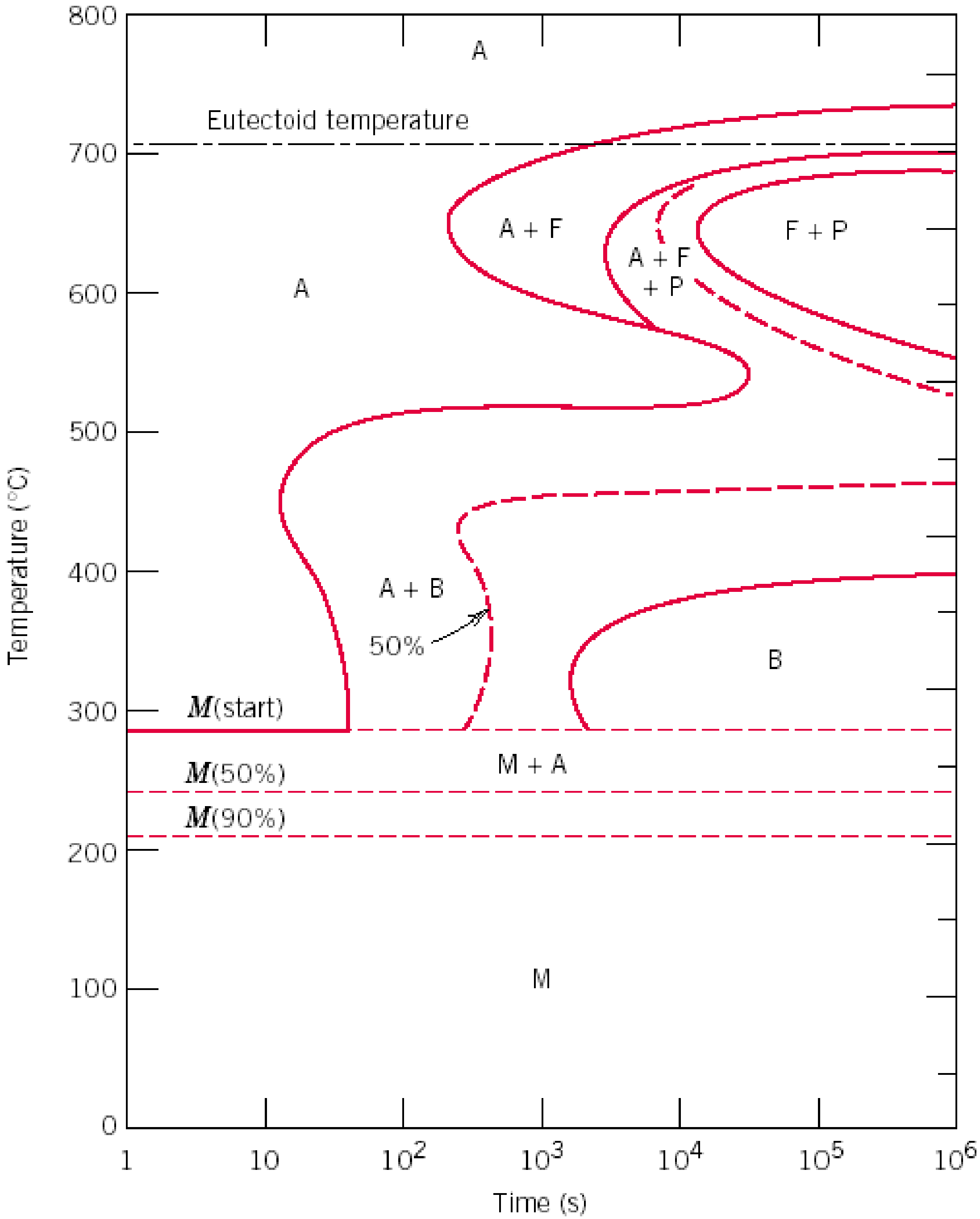
M: martensite

P: pearlite

The Martensitic Transformation

Since the martensitic transformation is instantaneous, it is not depicted in this diagram like the pearlitic reaction.

- The beginning of this transformation is represented by a horizontal line designated M(start).
- Two other horizontal and dashed lines, labeled M(50%) and M(90%), indicate percentages of the austenite-to-martensite transformation.
- The temperatures at which these lines are located vary with alloy composition; the temperatures must be relatively low.
- The horizontal and linear character of these lines indicates that the martensitic transformation is independent of time; it is a function only of the temperature to which the alloy is quenched.



Effects of alloying elements

The presence of alloying elements other than carbon (e.g., Cr, Ni, Mo, and W) may cause significant changes in the positions/shapes of the curves in the isothermal transformation diagrams.

TTT diagram for an alloy steel (type 4340):

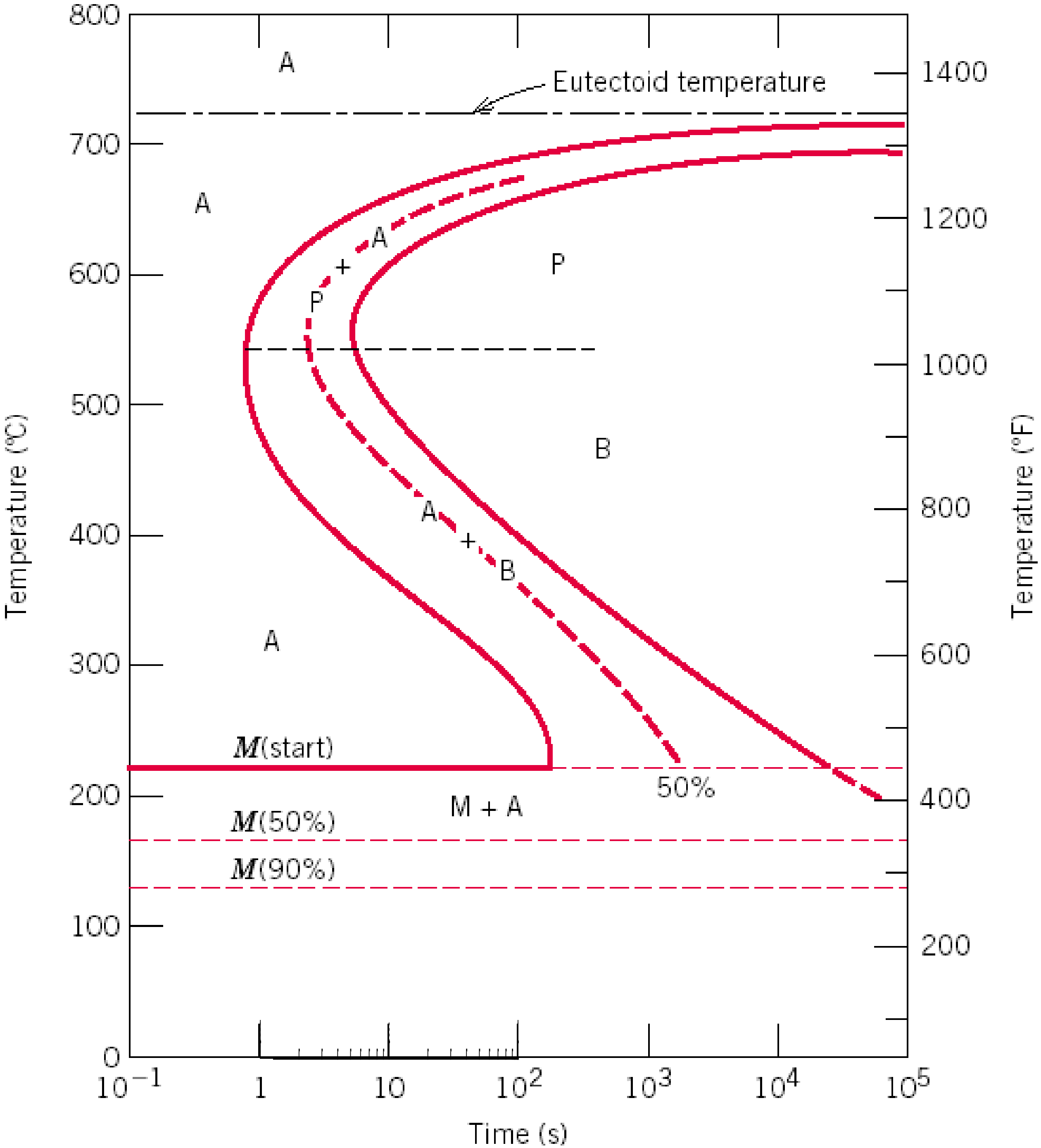
A, austenite;

B, bainite;

P, pearlite;

M, martensite;

F, proeutectoid ferrite.



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

A: austenite

B: bainite

M: martensite

P: pearlite

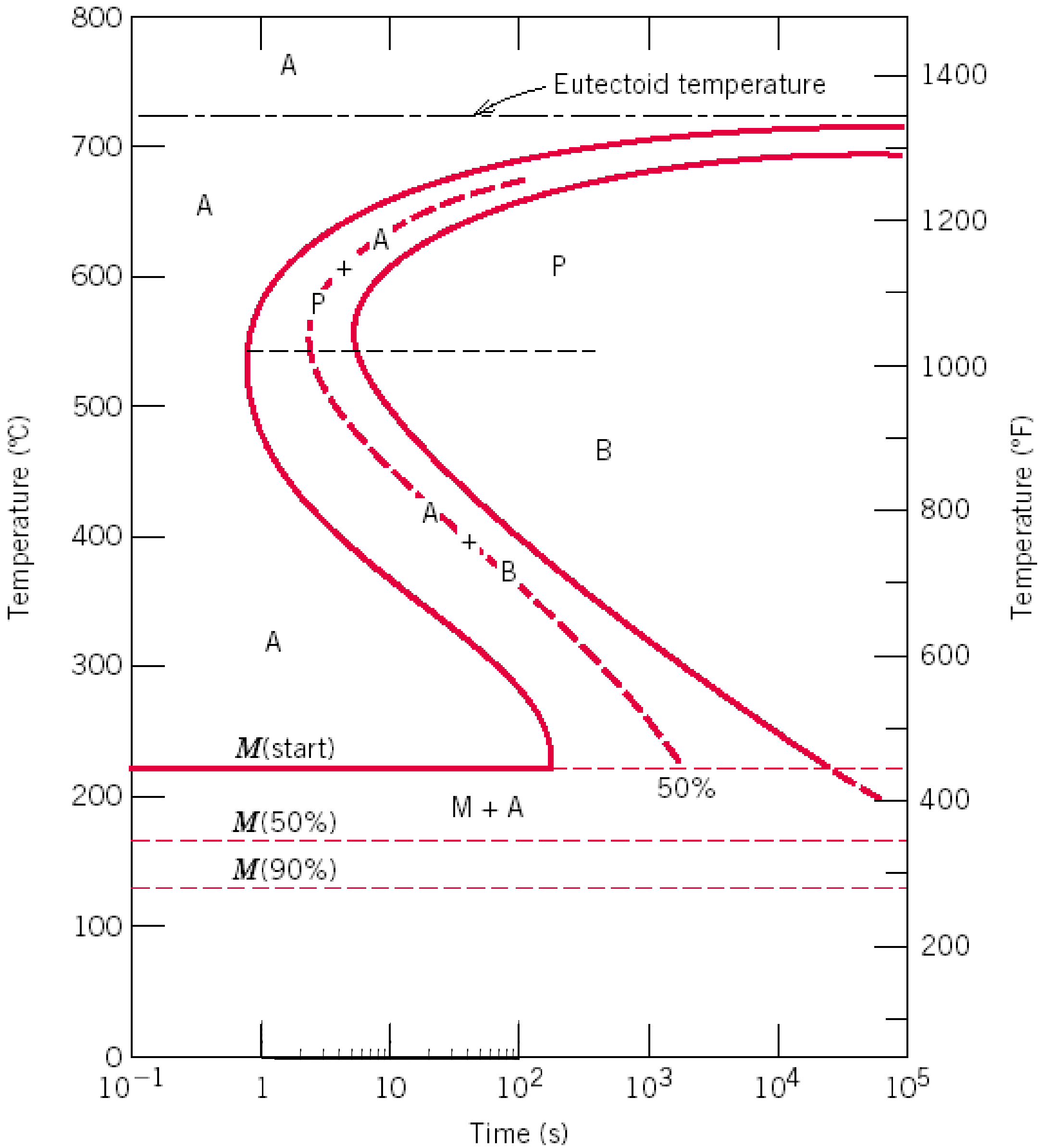
Example Problem

Using the isothermal transformation diagram for an iron-carbon alloy of eutectoid composition, specify the nature of the final microstructure of a small specimen that has been subjected to the following time-temperature treatments.

The specimen begins at 760°C and that it has been held at this temperature long enough to have achieved a complete and homogeneous austenitic structure.

(a) Rapidly cool to 250°C, hold for 100s, and quench to room temperature

(b) Rapidly cool to 600°C, hold for 10^4 s, and quench to room temperature

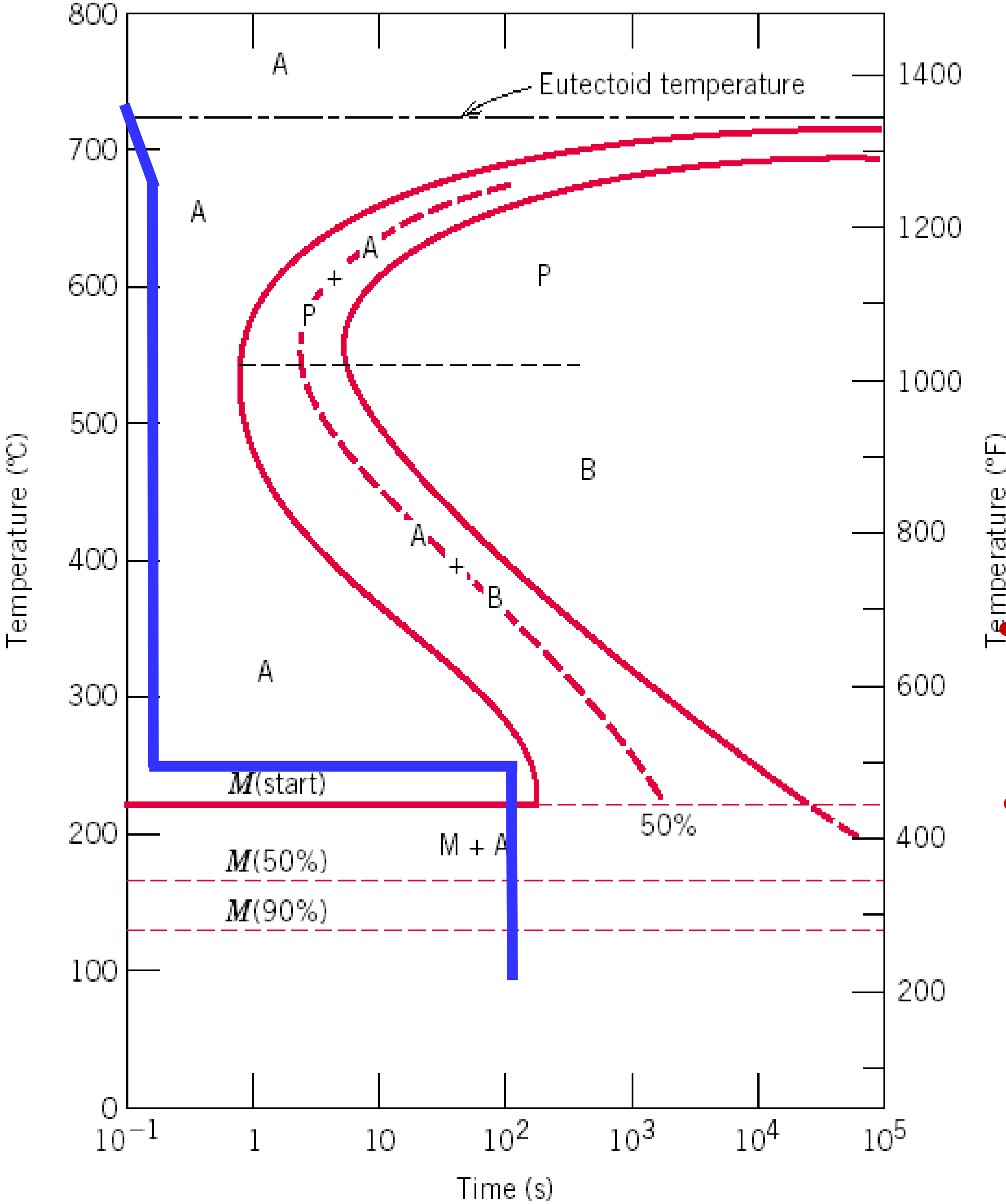


Example Problem

(a) Rapidly cool to 250°C, hold for 100s, and quench to room temperature

(b) Rapidly cool to 600°C, hold for 10^4 s, and quench to room temperature

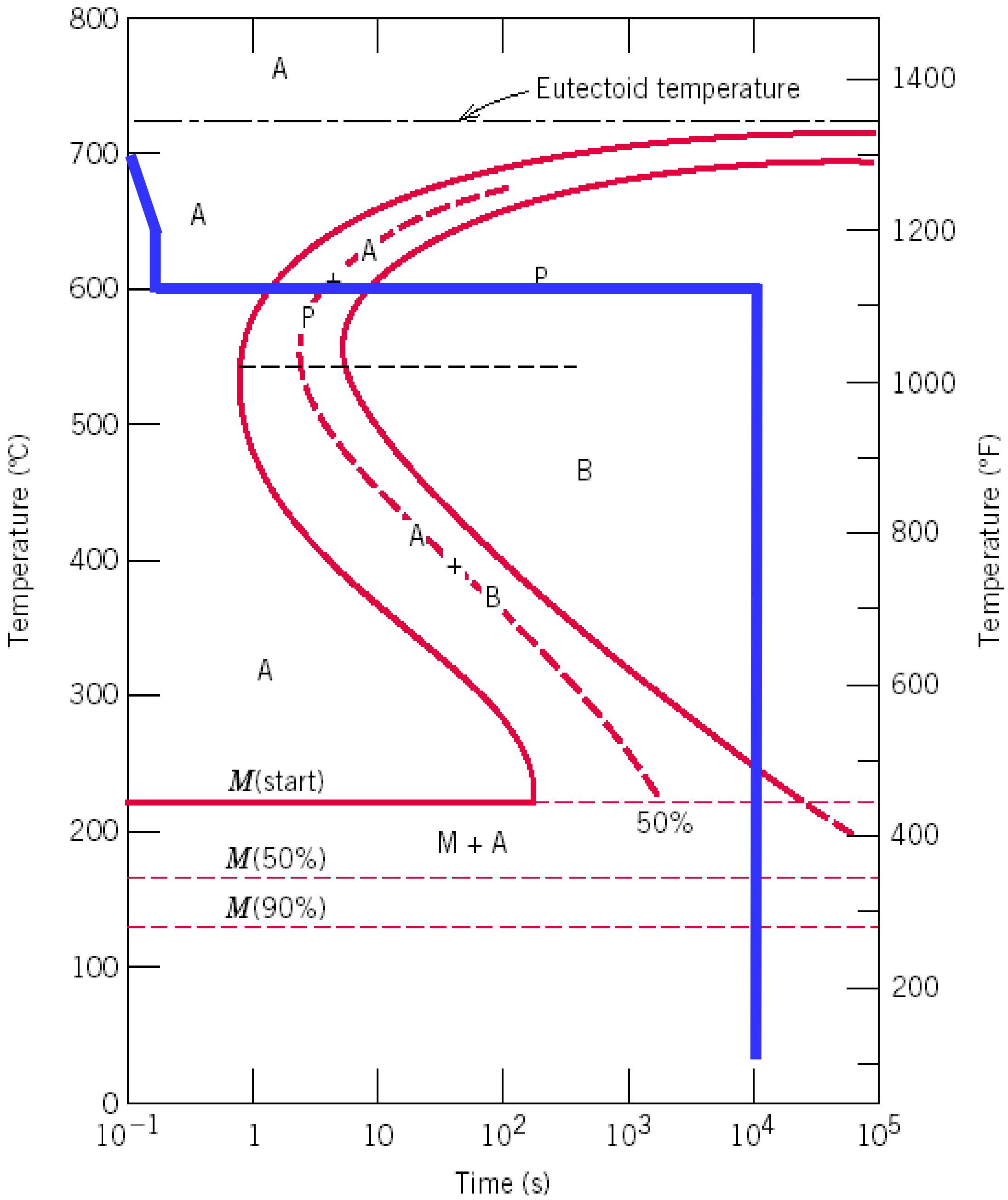
The time-temperature-transformation diagram for an iron-carbon alloy of eutectoid composition and the isothermal heat treatments



Example Problem

(a) Rapidly cool to 250°C, hold for 100s, and quench to room temperature

- **At 760°C: in the austenite region (γ)—100% austenite**
- **Rapidly cool from 760°C to 250°C: 100% austenite**
- **Hold for 100 seconds at 250°C: 100% austenite**
- **Quench to room temp.: 100% martensite**



Example Problem

(b) Rapidly cool to 600°C, hold for 10^4 s, and cool to room temperature

- **At 760°C: in the austenite region (γ)—100% austenite**
- **Rapidly cool from 760°C to 600°C: 100% austenite**
- **Hold for 10^4 s at 250°C: 100% pearlite**
- **Quench to room temp.: 100% pearlite**

Mechanical Behavior of Iron-Carbon Alloys

Pearlite

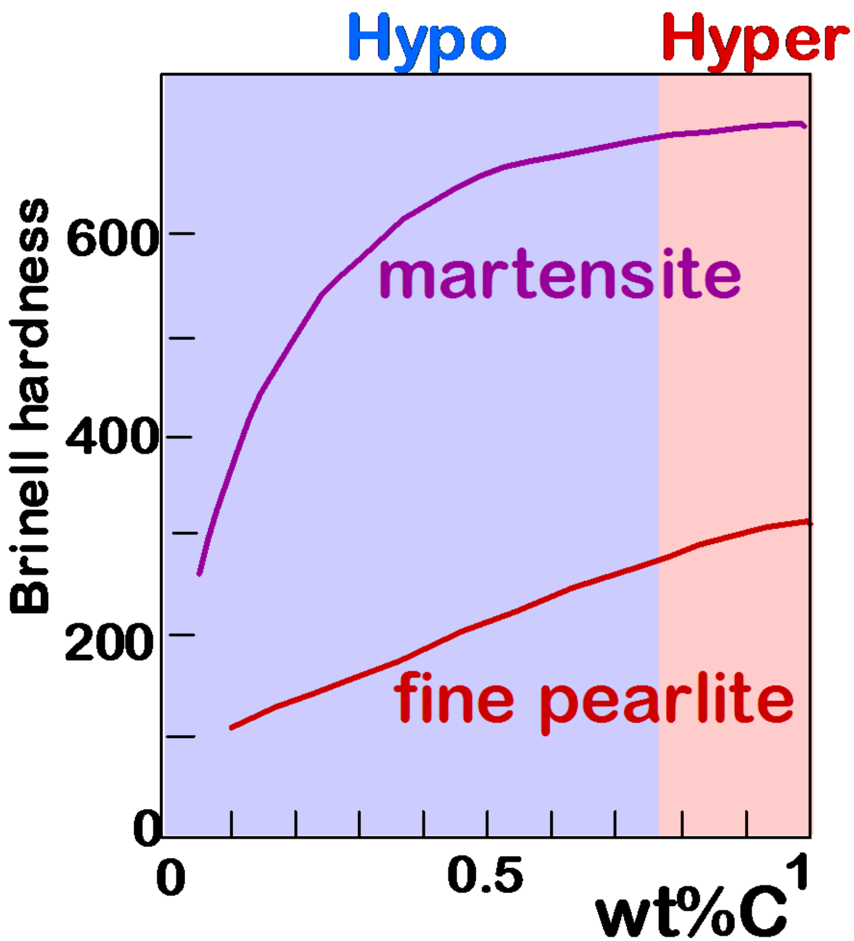
- **Cementite (Fe_3C) is much harder but more brittle than ferrite (α).**
- **% $Fe_3C \uparrow \Rightarrow$ strength$\uparrow$, ductility$\downarrow$**

Martensite

- **Hardest and strongest, and most brittle**
- **Volume change $\rightarrow$ crack formation during quenching**

Mechanical Properties of Fe-C Systems

- **Fine Pearlite vs Martensite:**



- **Hardness: fine pearlite << martensite.**