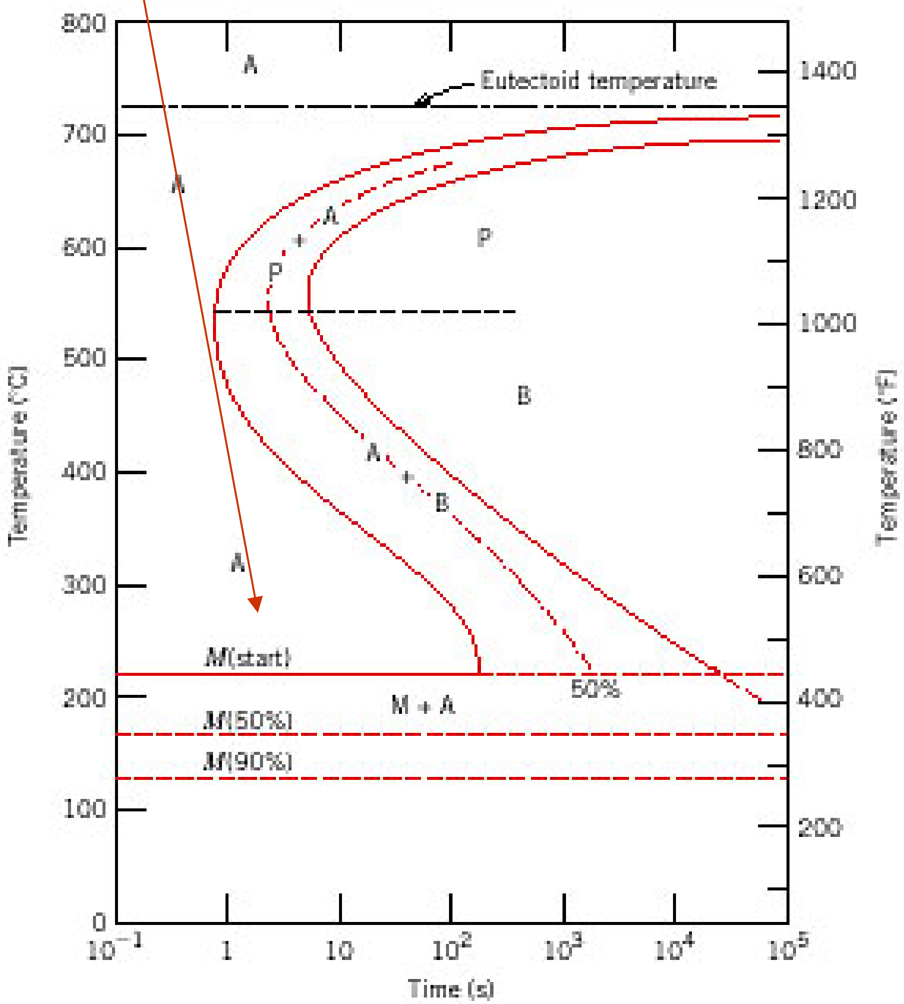
Martensite

Athermal transformation



Massive martensite

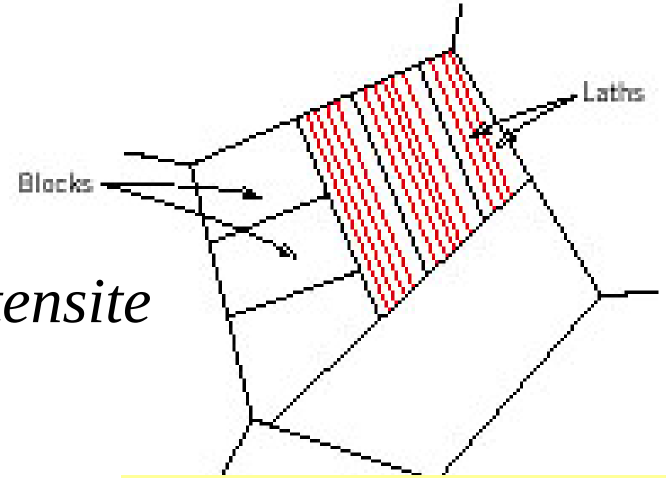
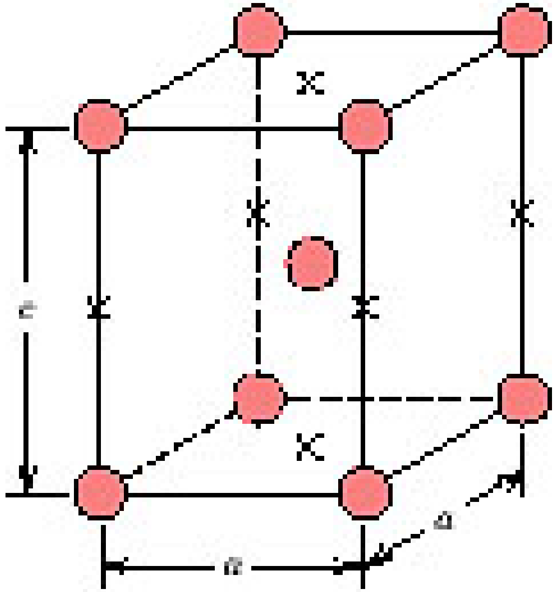


Plate martensite



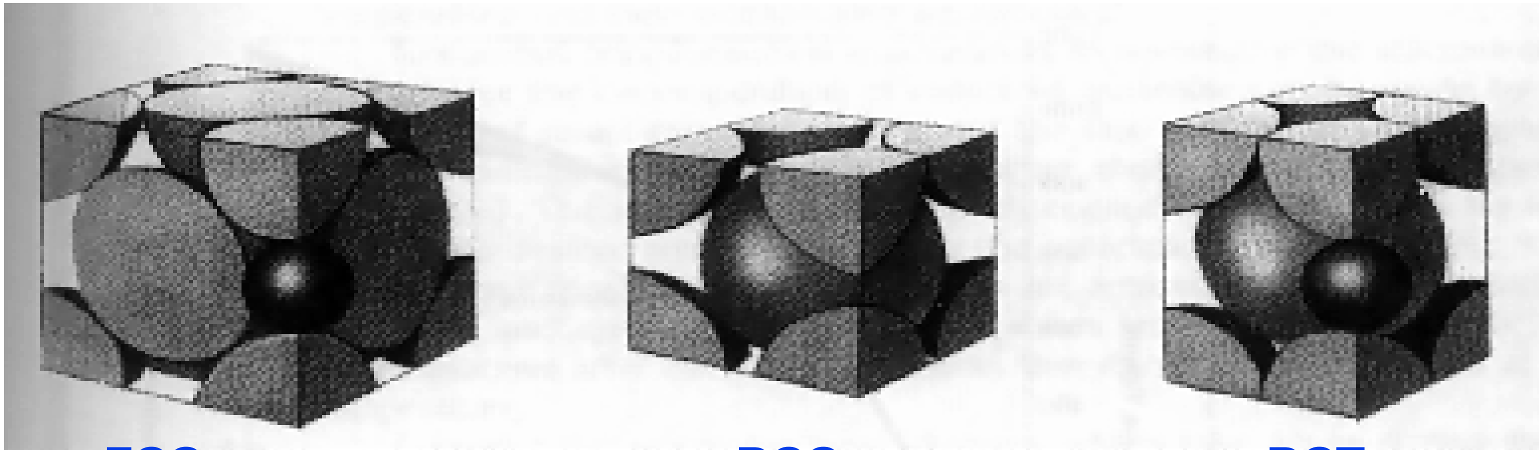
Body centered tetragonal (BCT) structure.

“M_s” stands for “*Martensite Start Temperature*” and

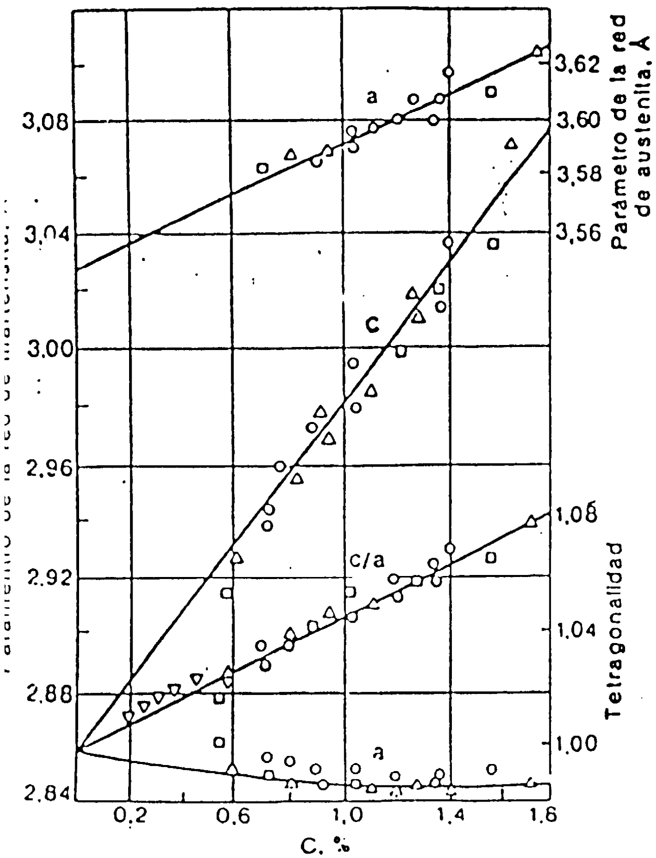
“M_f” stands for “*Martensite Finished Temperature*”.

Due to the fast cooling, diffusion of carbon is restricted. To make room for the carbon atoms, the lattice stretches along one crystal direction.

Martensite is a metastable phase.



FCC BCC BCT



Martensite is a supersaturated solution of carbon in iron.

Due to the high lattice distortion, martensite has high residual stresses.

The high lattice distortion induces high hardness and strength to the steel.

However, ductility is loss (martensite is too brittle) and a post heat treatment is necessary.

Heat treatment

Examples

(a) rapidly cool to 350°C; hold 10^4s and then quench to room temp.

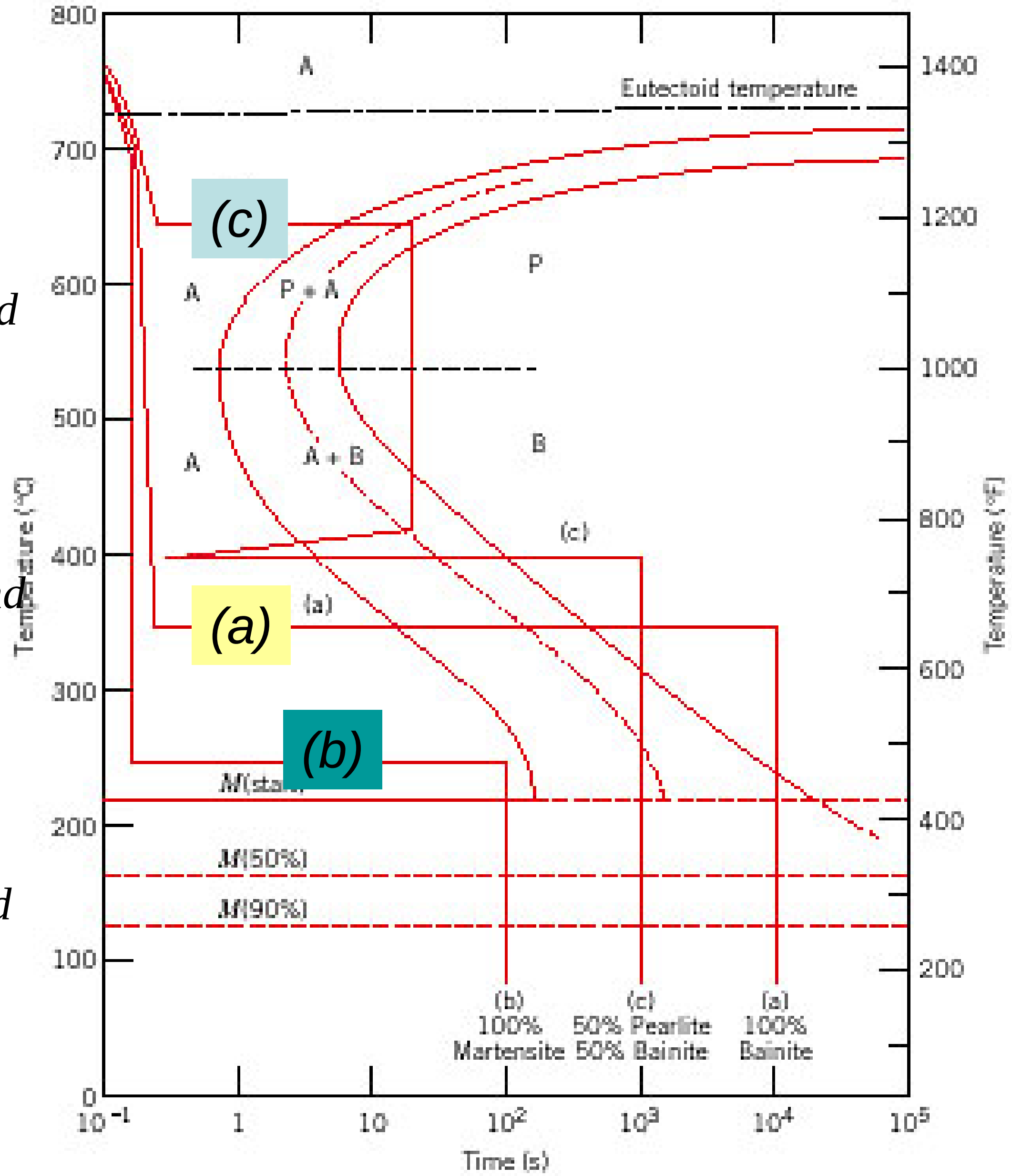
100% bainite

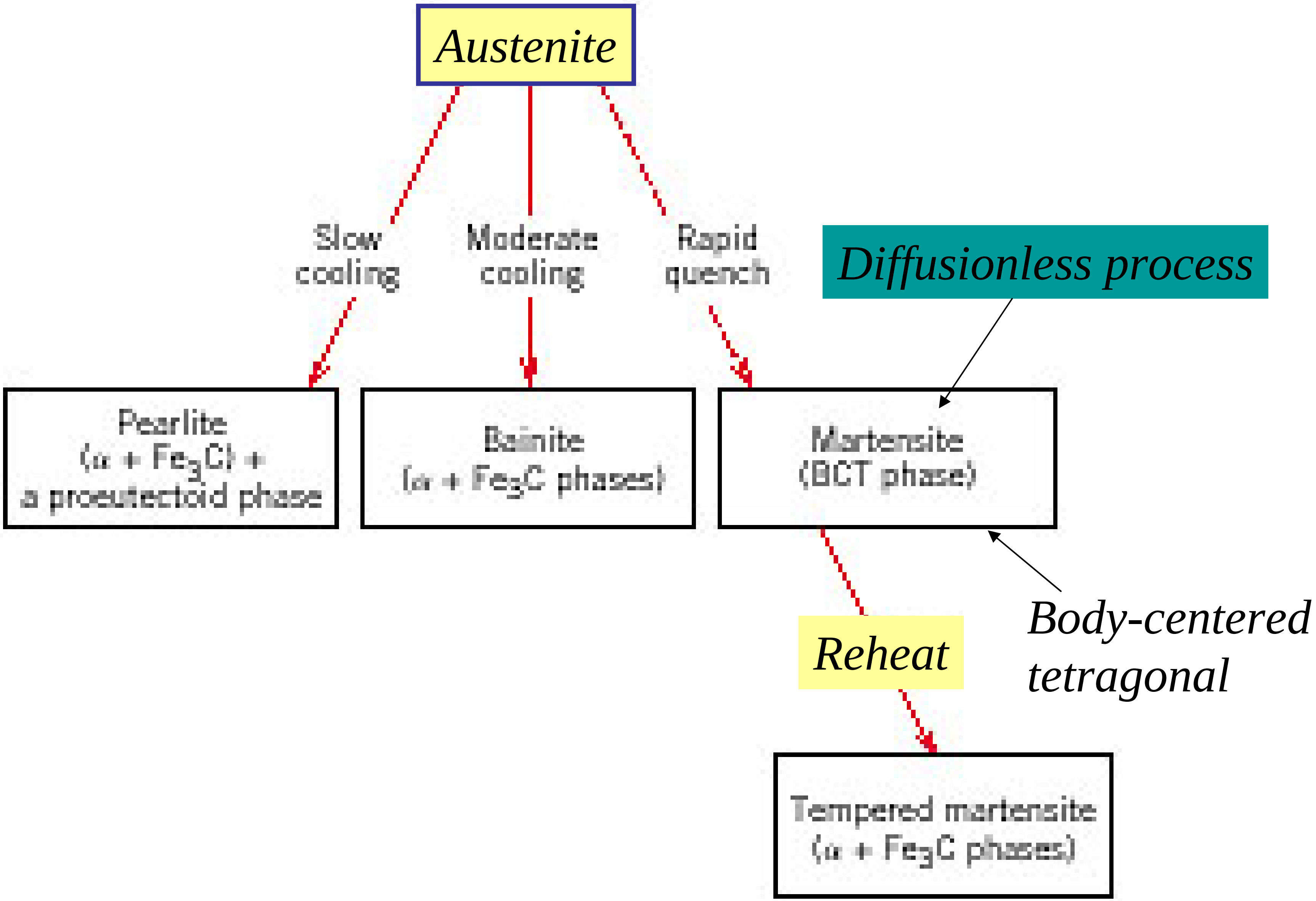
(b) rapidly cool to 250°C; hold 100s and then quench to room temp.

100% martensite

(c) rapidly cool to 650°C; hold 20s and rapidly cool to 400°C, hold 103s, and and then quench to room temp.

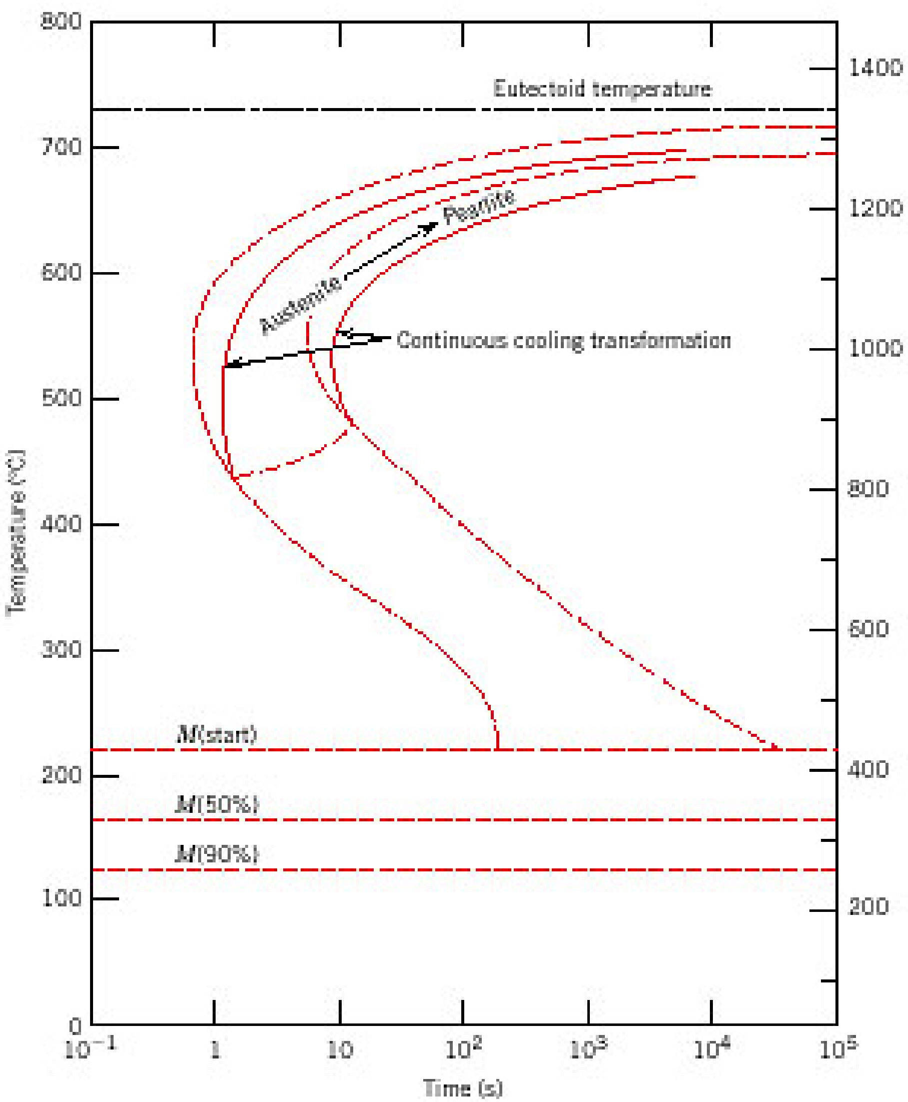
50% pearlite + 50% bainite

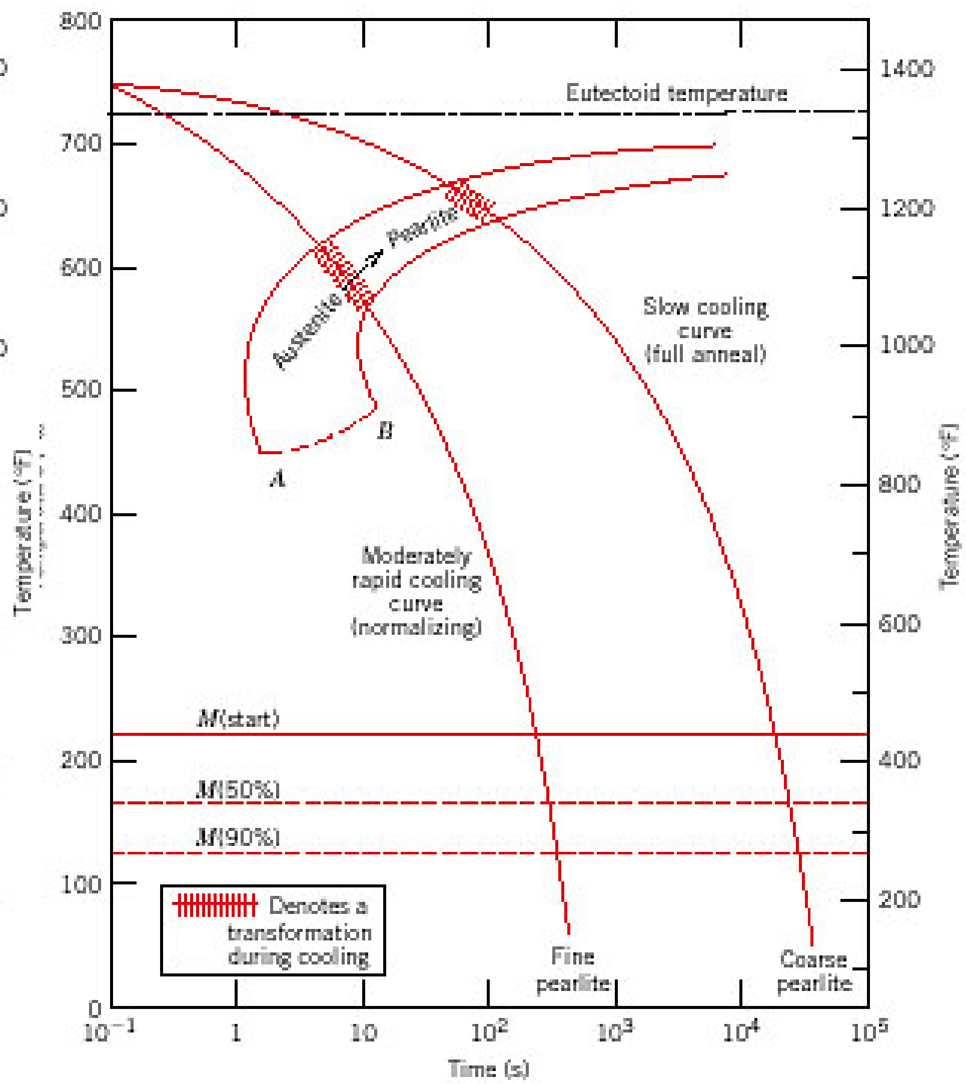




Temper embrittlement : reduction of toughness after tempering

Continuous Cooling Transformation *+ cooling curve*





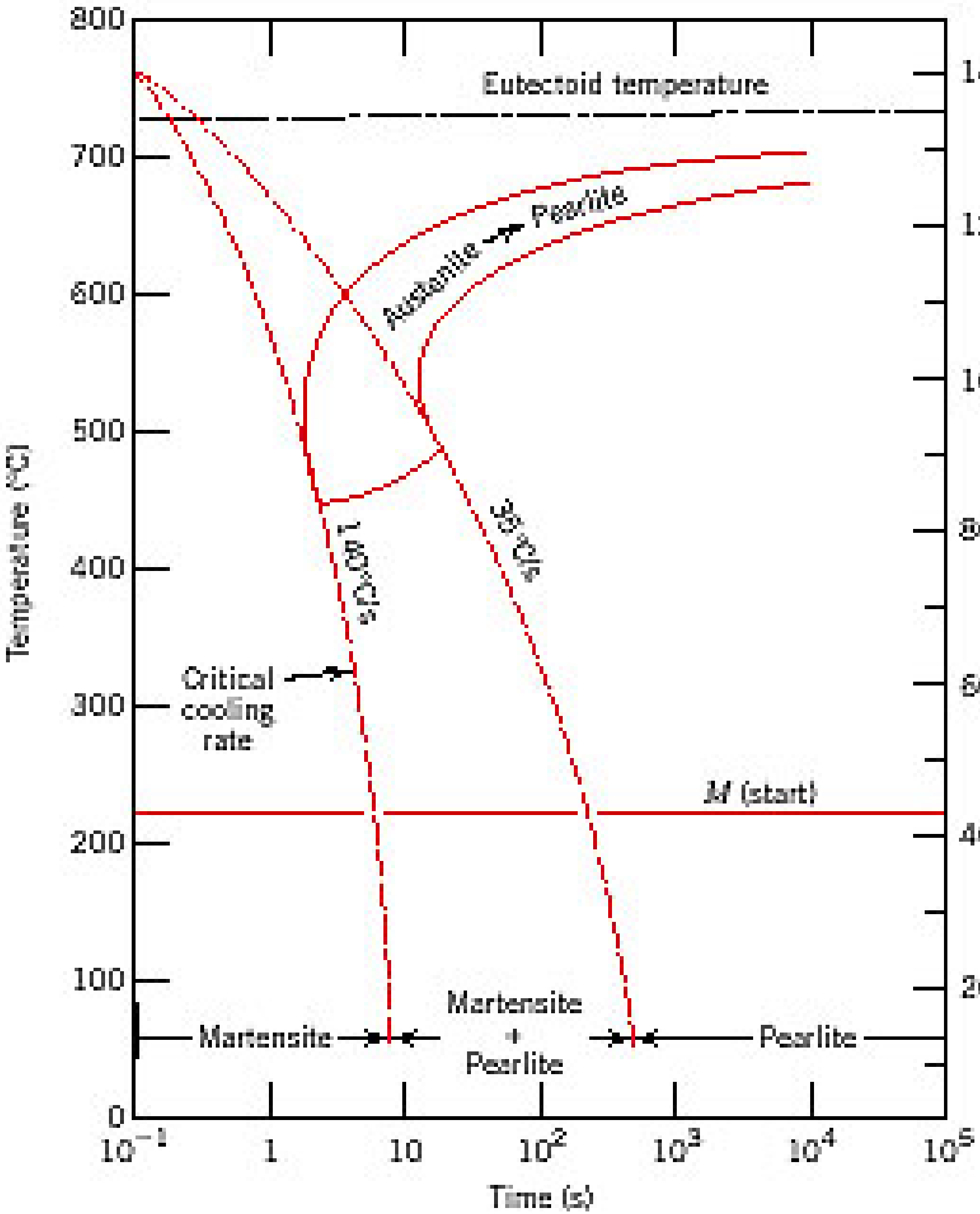


FIGURE 10.19 Continuous cooling transformation diagram for a eutectoid iron–carbon alloy and superimposed cooling curves, demonstrating the dependence of the final microstructure on the transformations that occur during cooling.

Control of final structures

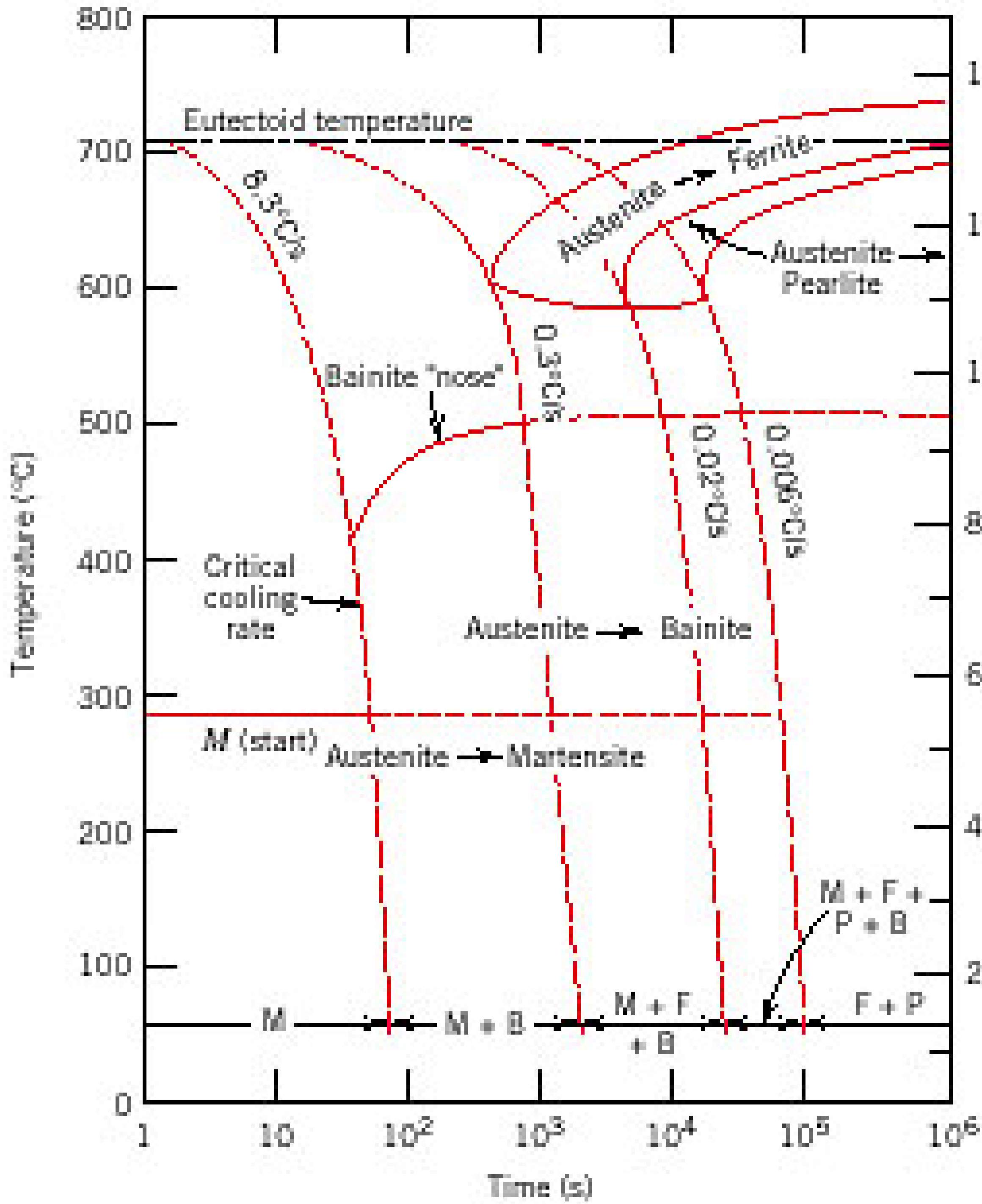


FIGURE 10.20 Continuous cooling transformation diagram for an alloy steel (type 4340) and several superimposed cooling curves demonstrating dependency of the final microstructure of this alloy on the transformations that occur during cooling. (Adapted from H. E. McGannon, Editor, *The Making, Shaping and Treating of Steel*, 9th edition, United States Steel Corporation, Pittsburgh, 1971, p. 1096.)

Common Industrial Heat Treatments

- **Annealing (slow cooling from austenitizing temperature. Product: coarse pearlite)**

- **Normalizing (air cooling from austenitizing temperature. Product: fine pearlite)**

- **Quench & Temper. Quench (fast – water or oil – cooling from austenitizing temperature. Product: martensite). Tempering (heating to $T < A_1$ to increase ductility of quenched steels)**

- **Martempering. (Quench to T above M_s and soak until all the steel section is at that temperature, then quench to ambient temperature. Product: Martensite)**

- **Austempering. (Quench to T above M_s and soak until phase transformation takes place. Product: Bainite**

Annealing

Stages of annealing:

- **Heating to required temperature**
- **Holding (“soaking”) at constant temperature**
- **Cooling**

The time at the high temperature (soaking time) is long enough to allow the desired transformation to occur.

Cooling is done slowly to avoid warping/cracking of due to the thermal gradients and thermo-elastic stresses within the or even cracking the metal piece.

Purposes of annealing:

- Relieve internal stresses
- Increase ductility, toughness, softness
- Produce specific microstructure

Examples of heat treatment

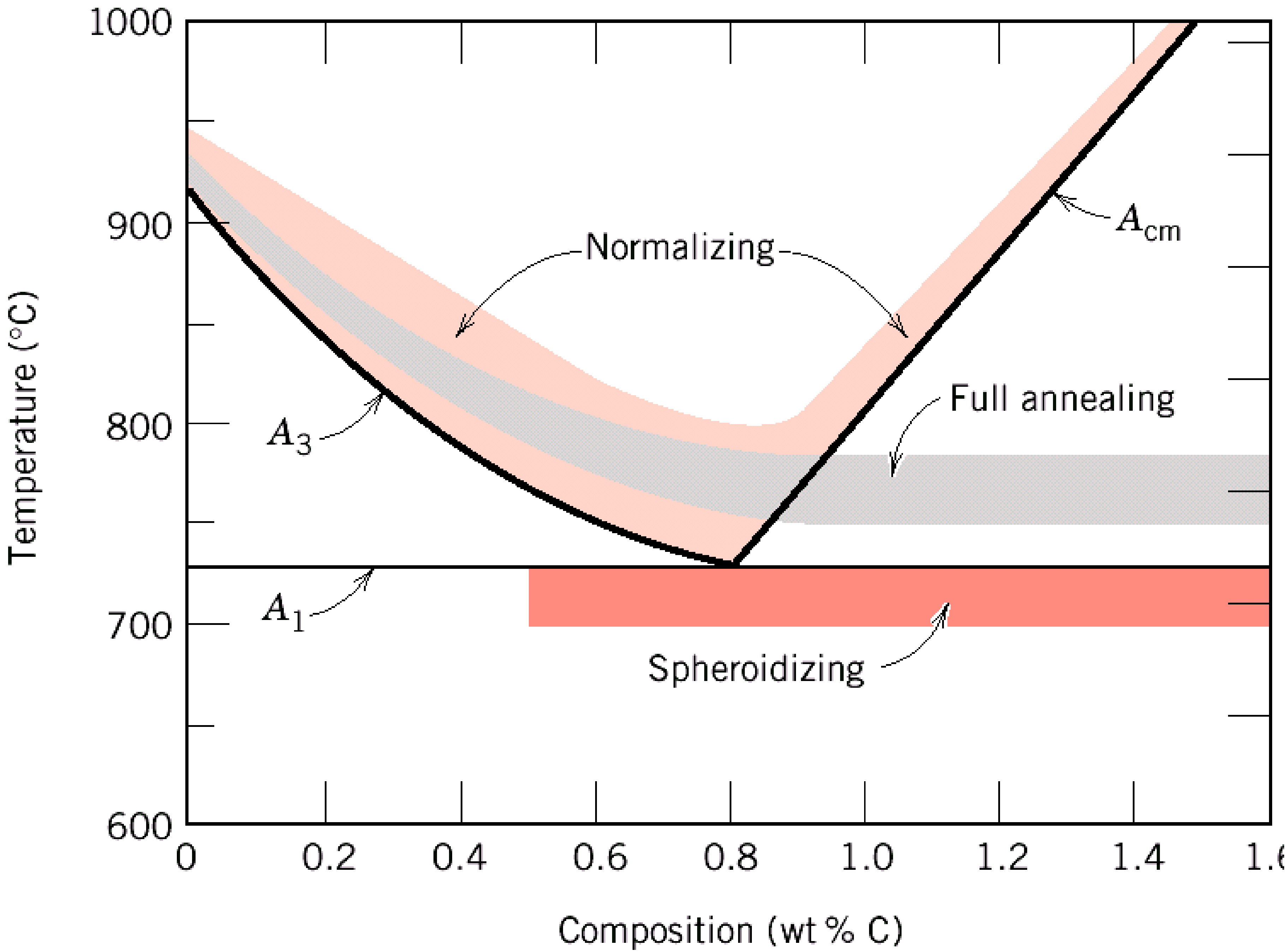
Process Annealing - effects of work-hardening (recovery and recrystallization) and increase ductility. Heating is limited to avoid excessive grain growth and oxidation.

Stress Relief Annealing – minimizes stresses due to

Plastic deformation during machining

- **Nonuniform cooling**
- **Phase transformations between phases with different densities**

Annealing temperatures are relatively low so that useful effects of cold working are not eliminated.



1000
900
800
700
600
Temperature (°C)
Normalizing
A_{cm}
Full annealing
A_3
A_1
Spheroidizing
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Composition (wt % C)

- **Lower critical temperature** A_1 below which austenite does not exist
- **Upper critical temperature** lines, A_3 and A_{cm} above which all material is austenite
- **Austenitizing** – complete transformation to austenite

Full annealing: austenizing and slow cooling (several hours). Produces coarse pearlite (and possible proeutectoid phase) that is relatively soft and ductile. It is used to soften pieces which have been hardened by plastic deformation, and which need to undergo subsequent machining/forming.

Temperatures for full annealing:

Hypoeutectoid steel : $A_3 + 50^oC$

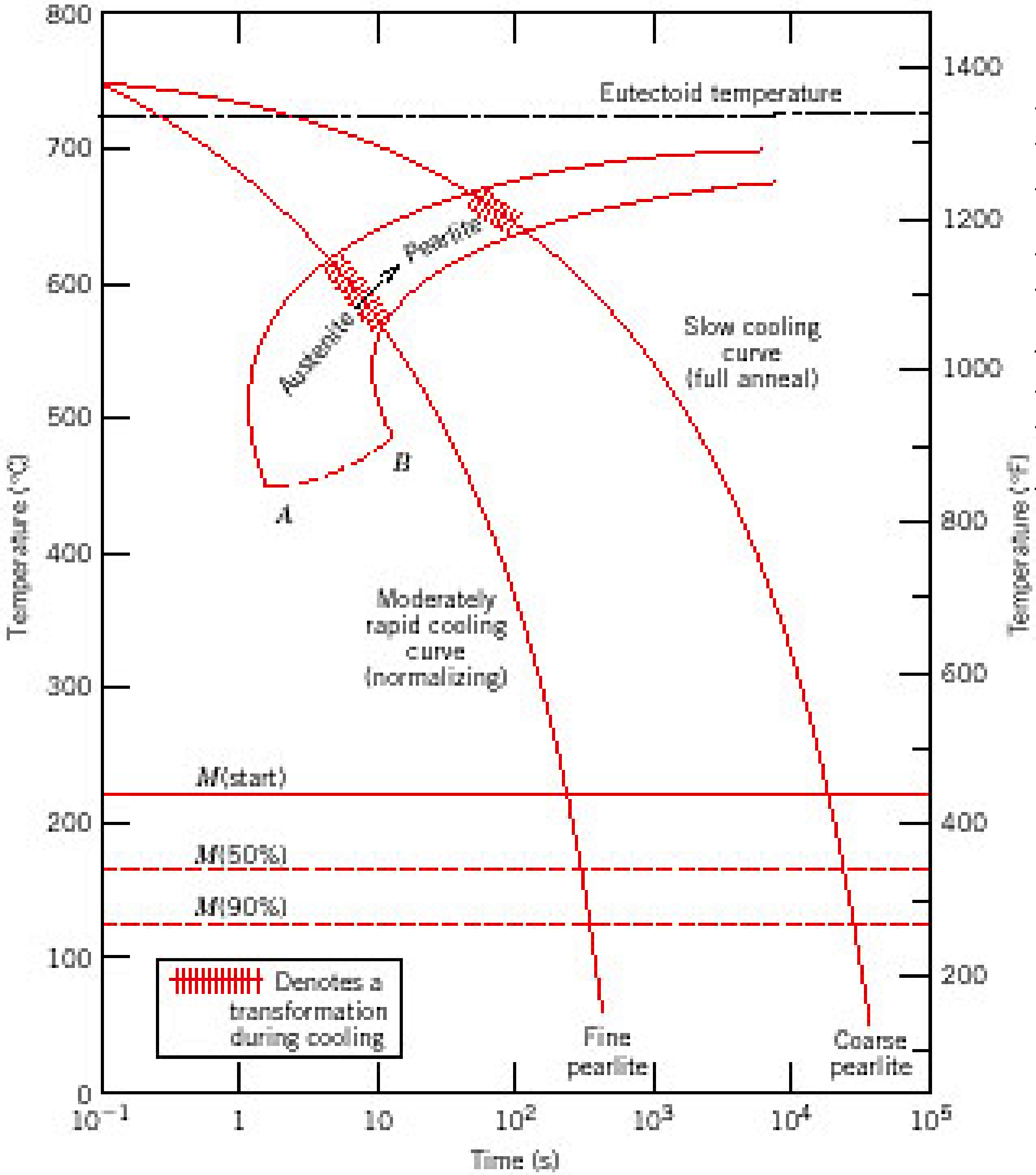
Hypereutectoid steel : $A_{1,3} + 50^oC$

Normalizing

Annealing heat treatment just above the upper critical temperature to reduce grain sizes (of pearlite and proeutectoid phase) and make more uniform size distributions.

The interlamellar distance of pearlite decreases as the cooling rate increases.

- **Slow cooling (annealing – furnace cooling) – coarse pearlite – interlamellar spacing of 4.5μm – hardness of 200BHN**
- **Medium to slow cooling (normalizing – still air cooling) – normal pearlite – interlamellar spacing of 3.0μm – hardness of 220BHN**
- **Medium to Fast (normalizing – forced air cooling) – fine pearlite – interlamellar spacing of 2.0μm – hardness of 300BHN**



Normalizing temperatures:

Hypoeutectoid steel : A_3 + 50ºC

Hypereutectoid steel : A_{cm} + 50ºC

Spheroidizing: **prolonged heating just below the eutectoid temperature, which results in the soft spheroidite structure. This achieves maximum softness needed in subsequent forming operations.**

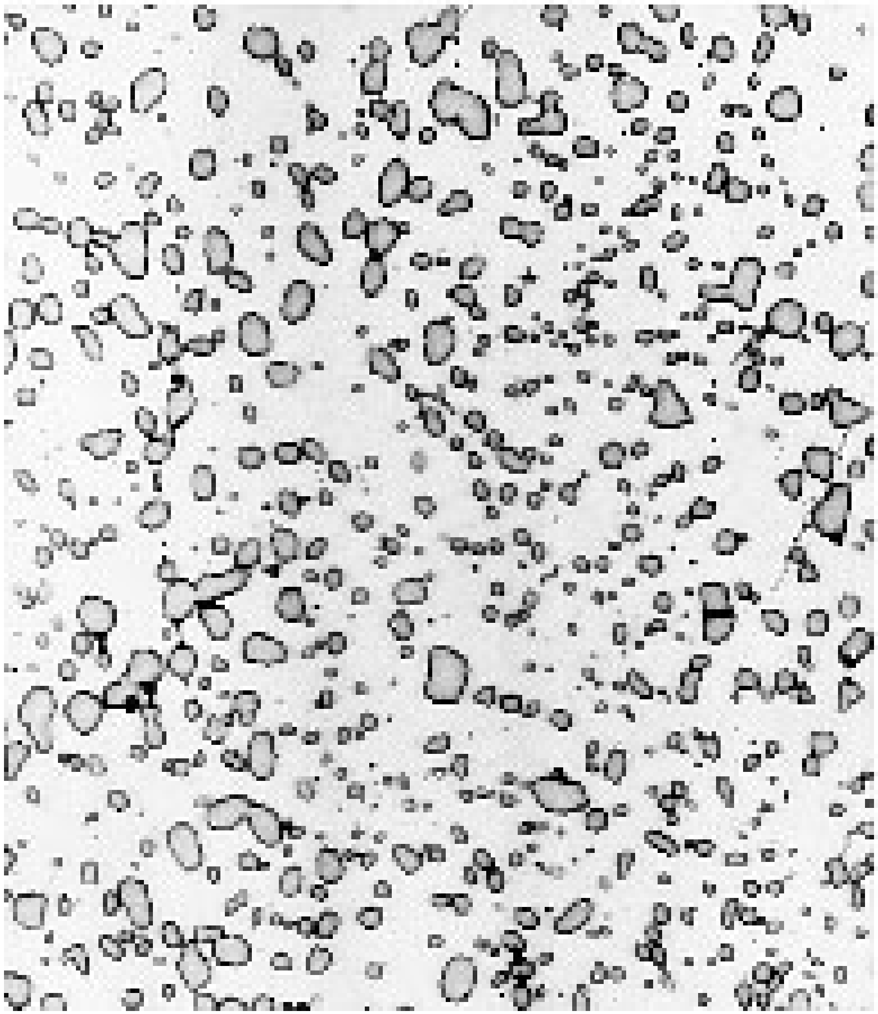


FIGURE 10.10 Photomicrograph of a steel having a spheroidite microstructure. The small particles are cementite; the continuous phase is α ferrite. 1000×. (Copyright 1971 by United States Steel Corporation.)

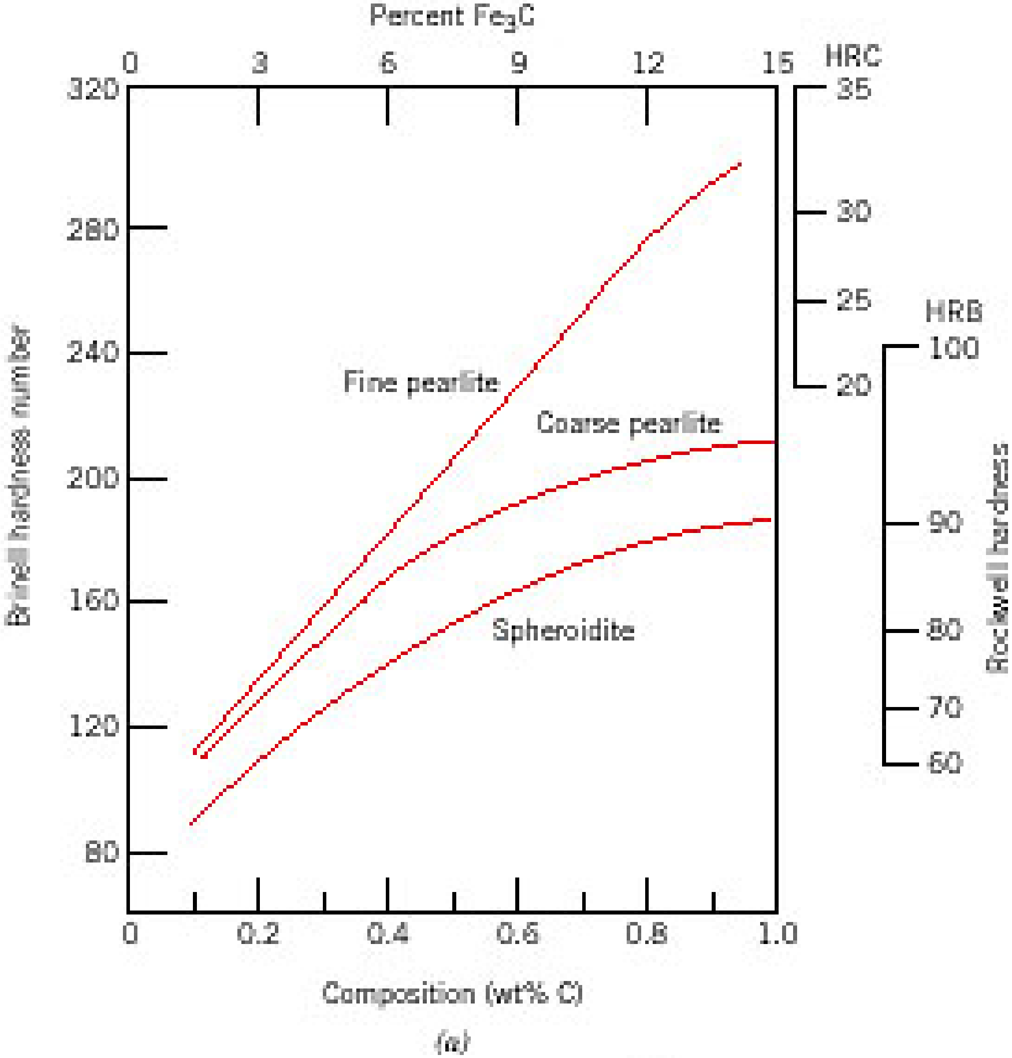
Pearlite or bainite $\xrightarrow{\text{Heating}}$ *Spheroidite*

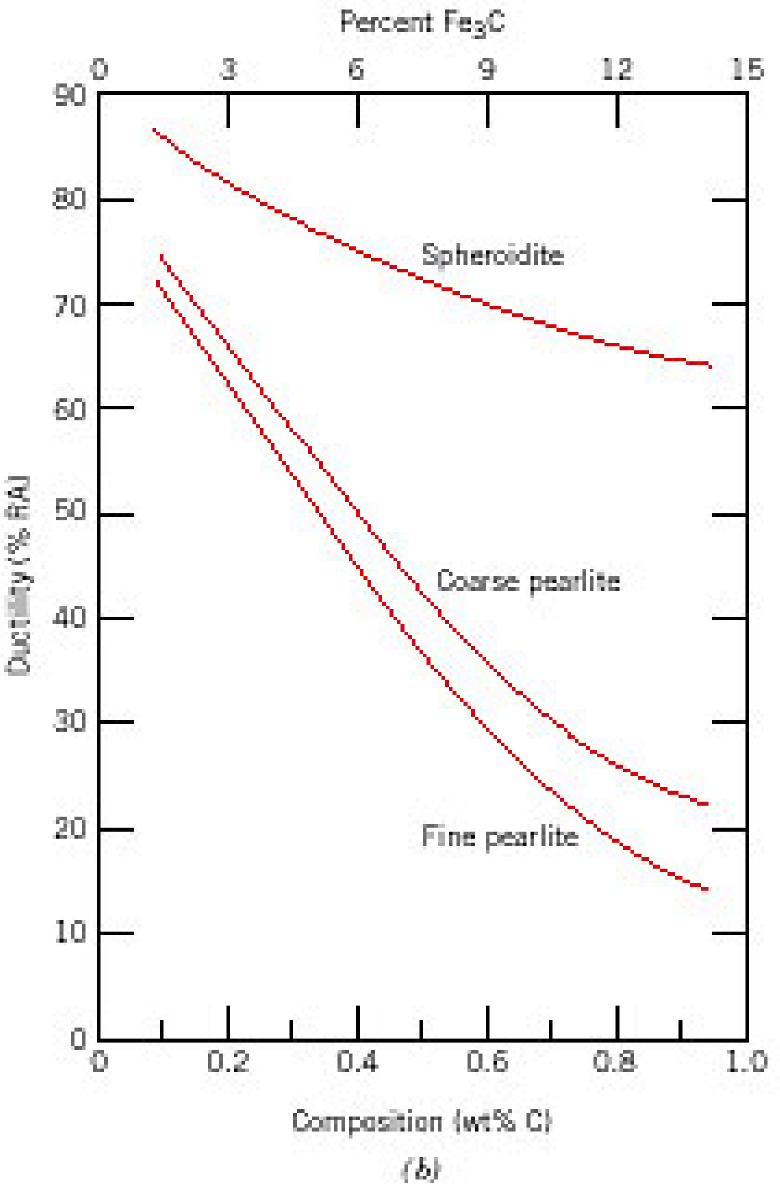
18~24h

below the eutectoid temp.

Reduction of α /Fe_3C GB area

Hardness and ductility





Quenching

The most common method to harden a steel.

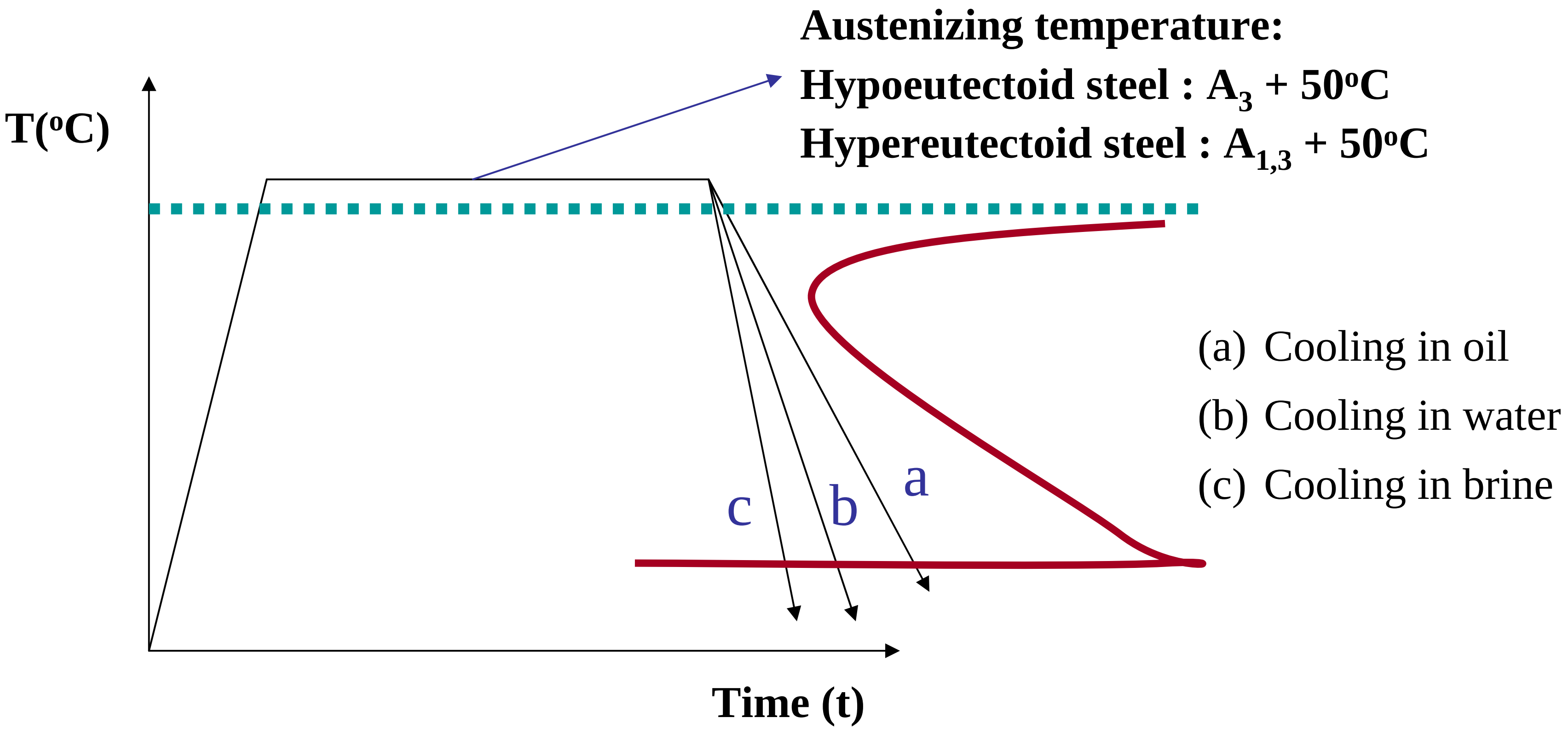
It consists of heating to the austenizing temperature (hypoeutectoid steel) and cooling fast enough to avoid the formation of ferrite, pearlite or bainite, to obtain pure martensite.

Martensite (α') has a distorted BCT structure. It is the hardest of the structures studied. The higher hardness is obtained at 100% martensite.

Martensite hardness depends solely of the carbon content of the steel. The higher the carbon content, the higher the hardness.

Martensite is very brittle and can not be used directly after quench for any application.

Martensite brittleness can be reduced by applying a post-heat treatment known as - *tempering*.



Cooling depends on the geometry and mass of the component.

External surfaces are cooled faster than the inner core of the component.

Tempering of Martensitic Steels

- Martensite is too brittle to serve engineering purpose
- Tempering is necessary to increase ductility and toughness of martensite. Some hardness and strength is lost.
- Tempering consist on reheating martensitic steels (solution supersaturated of carbon) to temperatures between 150-500º C to force some carbide precipitation.

1st stage 80-160º C

$$\alpha' \longrightarrow \alpha''\text{(low C martensite)} + \varepsilon_{carbide}\ (Fe_{2.3}C)$$

2nd stage 230-280º C

$$\gamma_{retained} \longrightarrow \text{bainite}$$

3rd stage 160-400º C

$$\alpha'' + \varepsilon_{carbide} \longrightarrow \alpha + Fe_3C\text{(tempered martensite)}$$

3rd stage (cont) 400-700ºC

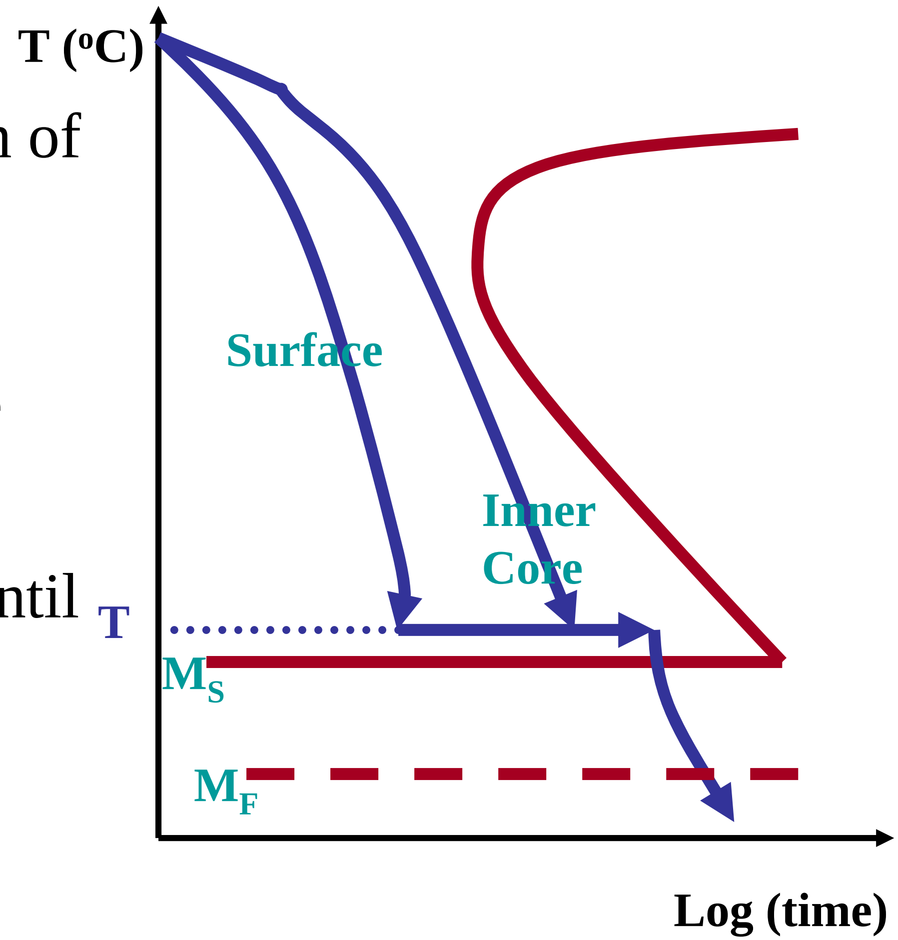
Growth and spherodization of cementite and other carbides

Martempering

A process to prevent the formation of quench cracks in the steel.

Cooling is carried out, as fast as possible, to a temperature over the M_S of the steel.

The steel is maintained at $T>M_S$ until the inner core and outer surface of the steel component is at the same temperature.



The steel is then cooled below the M_F to obtain 100% martensite. There is a need to increase the ductility of this steel by tempering.

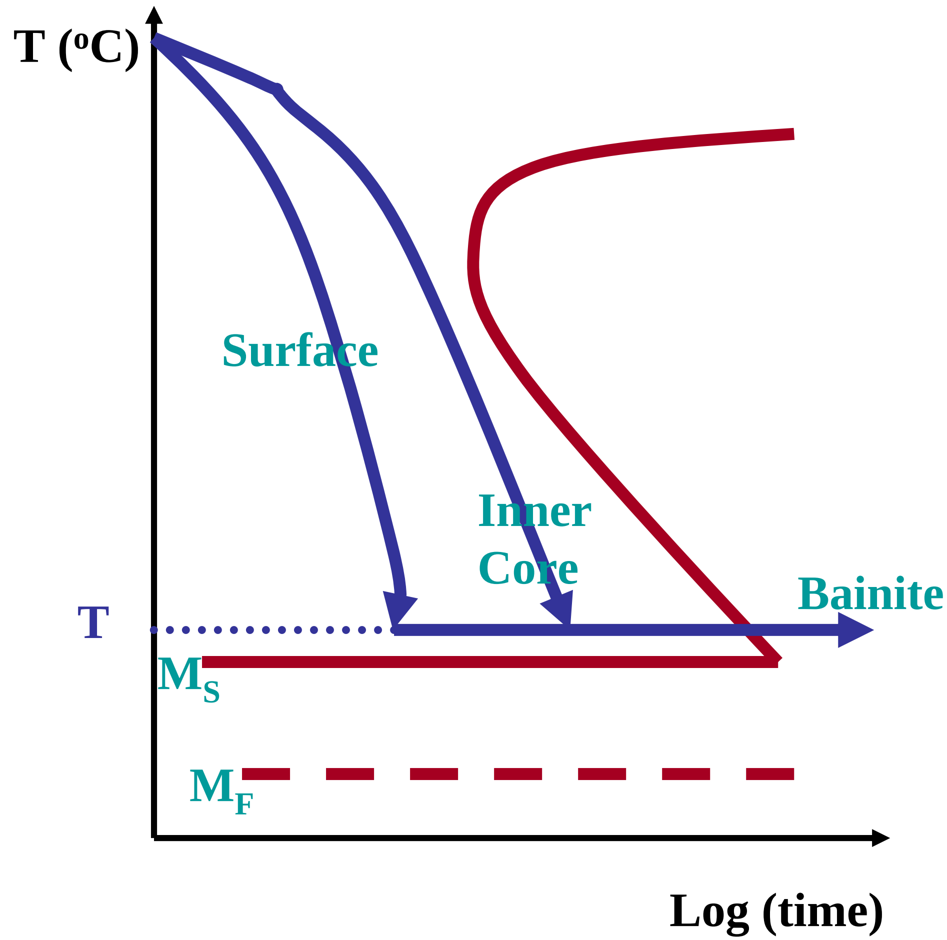
Austempering

A process to prevent the formation of quench cracks in the steel.

Cooling is carried out, as fast as possible, to a temperature over the M_S of the steel.

The steel is maintained at $T>M_S$ until the austenite transforms to 100% bainite.

There is no need of tempering post treatment.



Hardenability

Hardenability is the ability of the Fe-C alloy to transform to martensite during cooling. It depends on alloy composition and quenching media.

Hardenability should not be confused with "hardness". A qualitative measure of the rate at which hardness decreases with distance from the surface because of decreased martensite content.

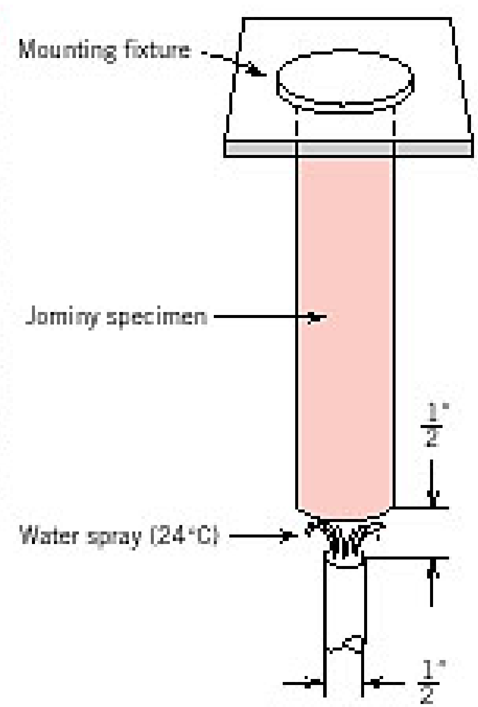
High hardenability means the ability of the alloy to produce a high martensite content throughout the volume of specimen.

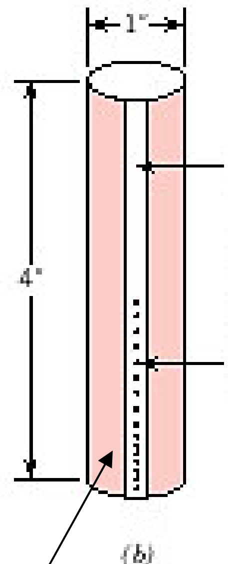
Hardenability is measured by the Jominy end-quench test performed in a standard procedure (cylindrical specimen, austenitization conditions, quenching conditions - jet of water at specific flow rate and temperature).

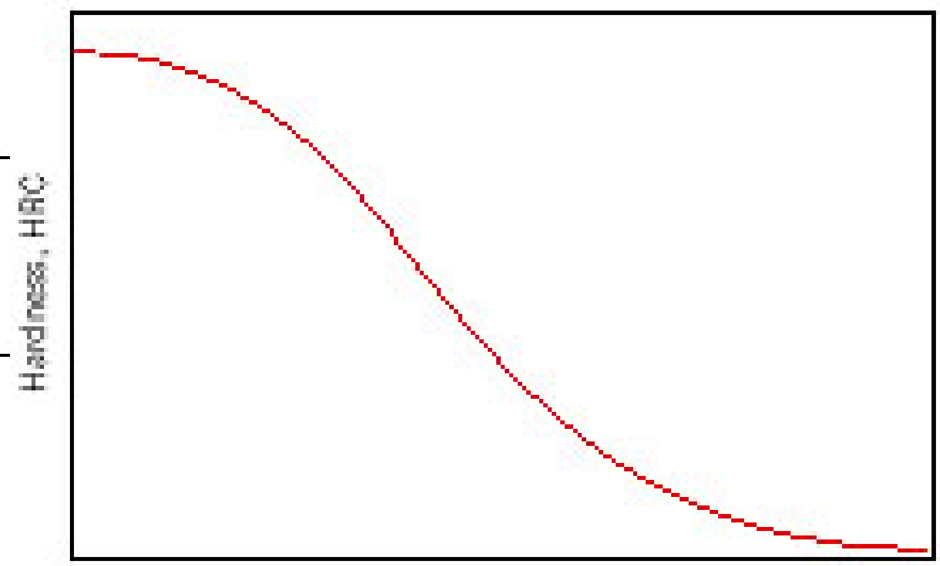
Hardenability

Ability to be hardened by the formation of martensite as a result of heat treatment

Jominy End-Quench Test







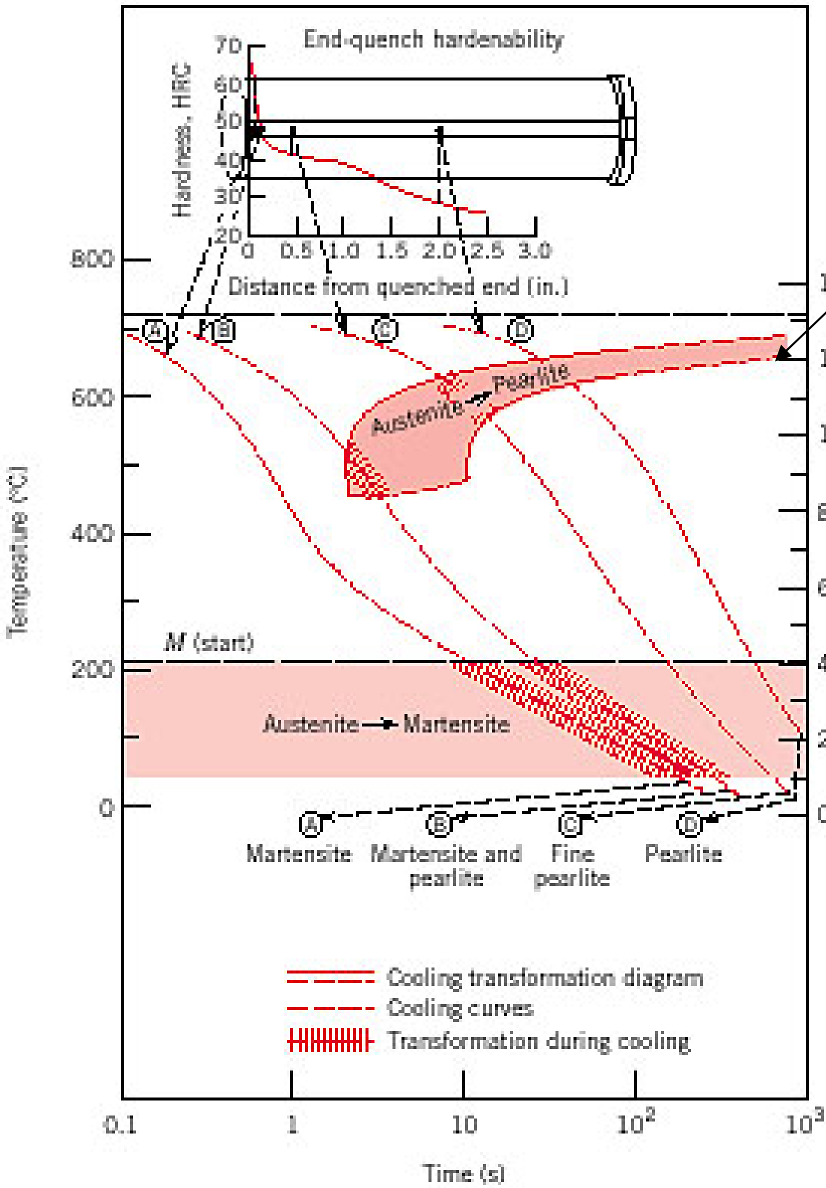
Distance from quenched end

Rockwell Hardness

Different Cooling rate !!

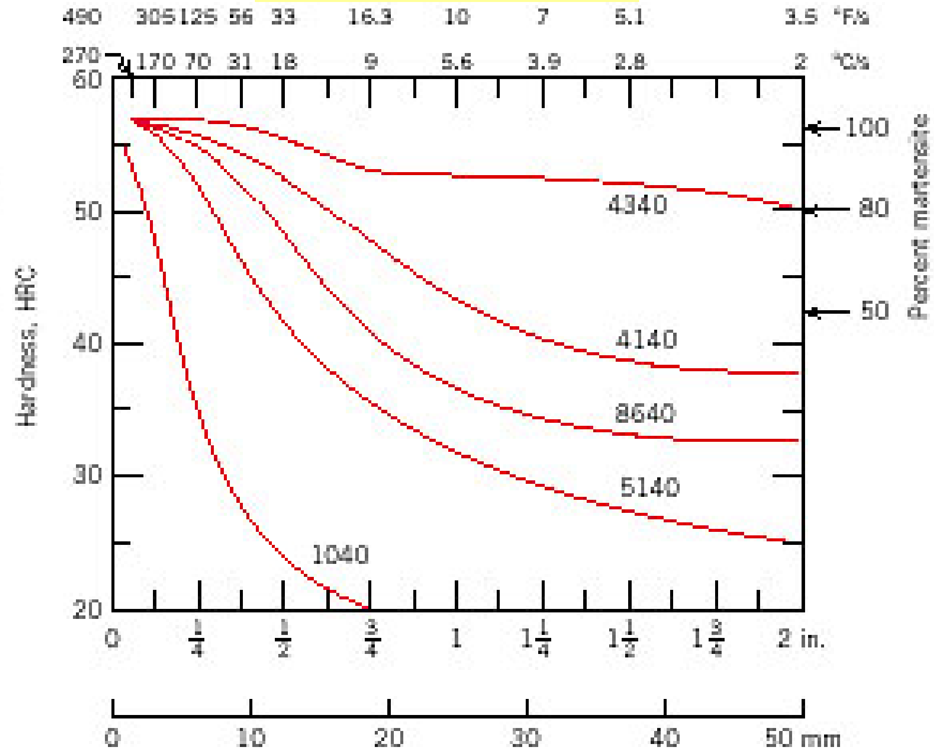
Hardness versus Cooling Rate

Continuous Cooling Transformation



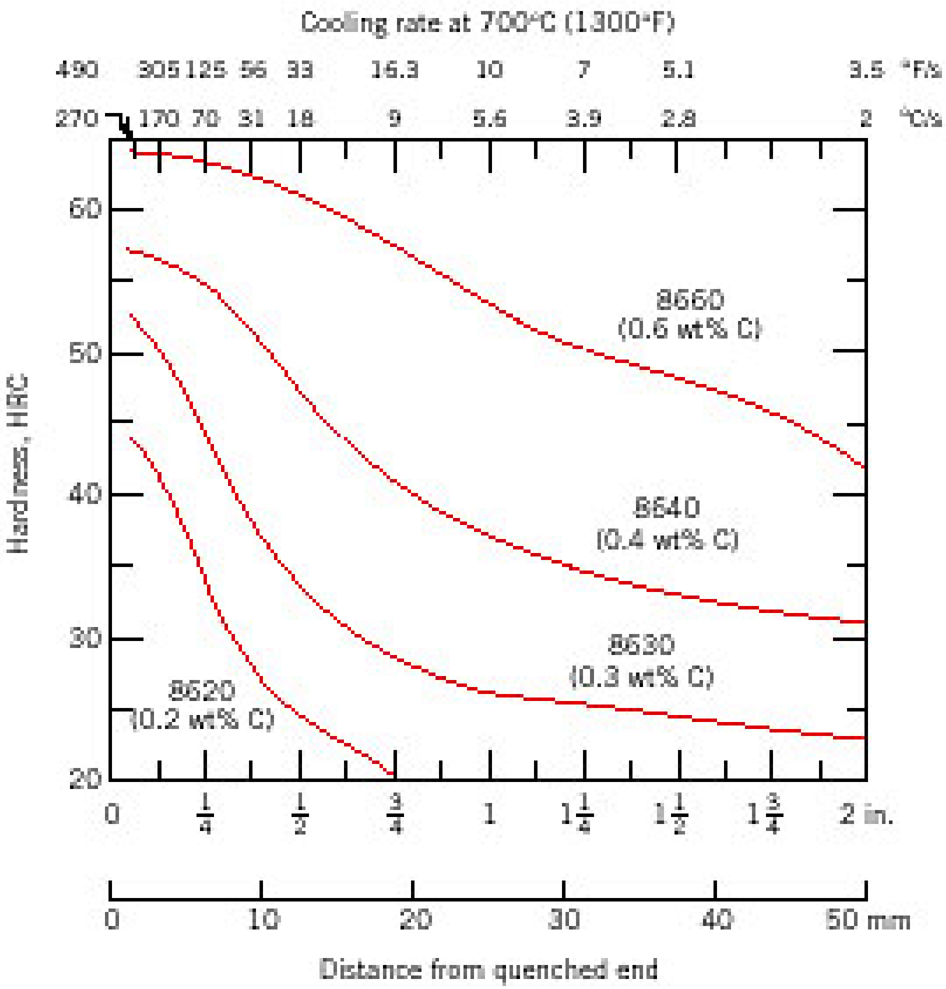
Hardenability Curve

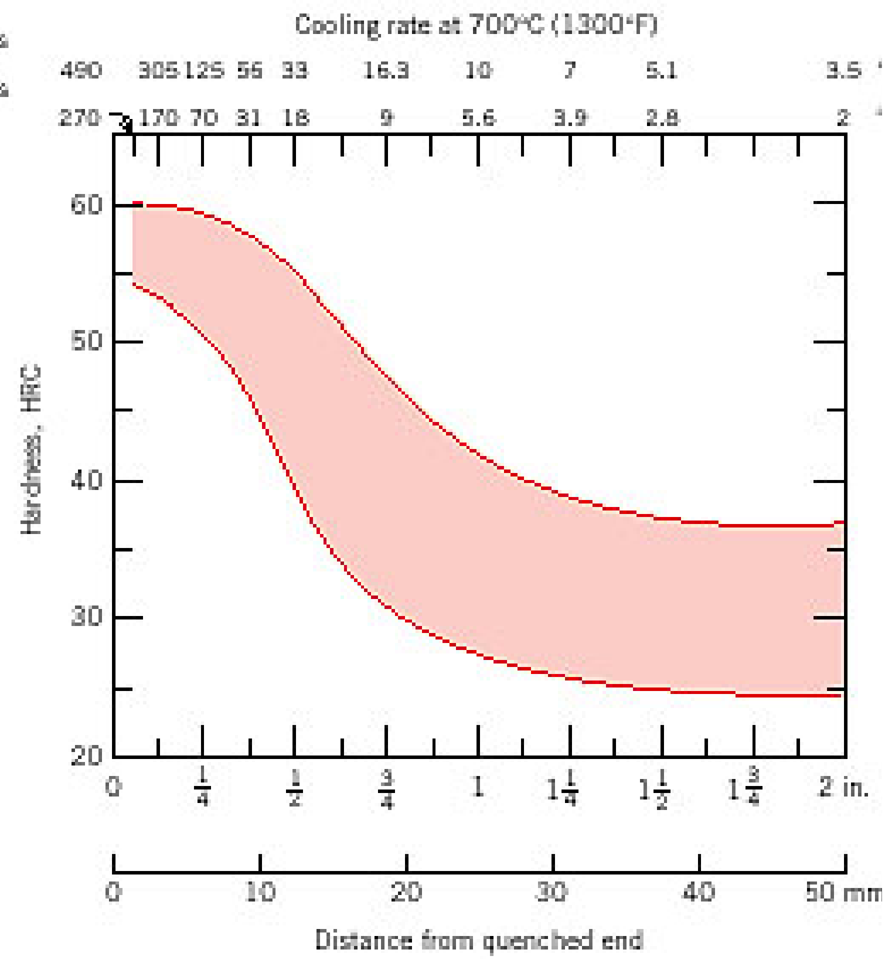
Cooling rate



Distance from quench end

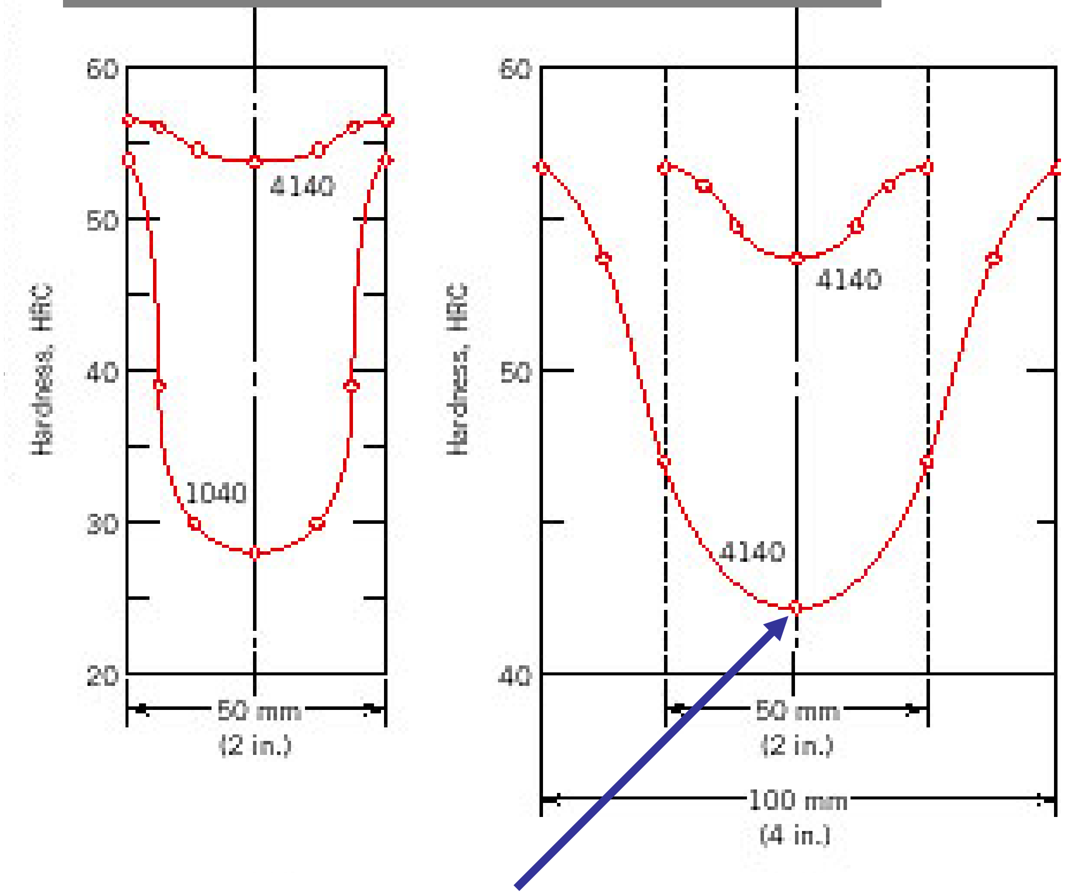
High carbon content, better hardenability



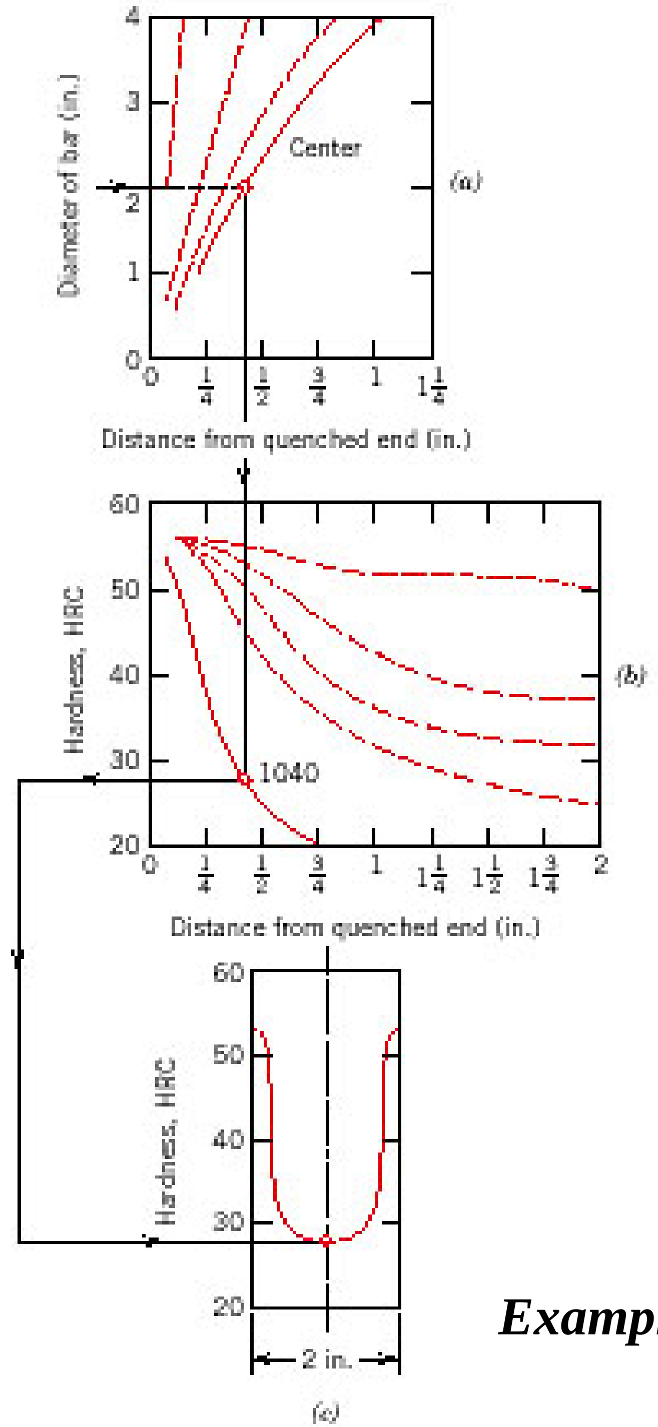


Use the hardenability data in the generation of hardness profile

Larger specimen, lower cooling rate



Closer to the center, lower the cooling rate



Example