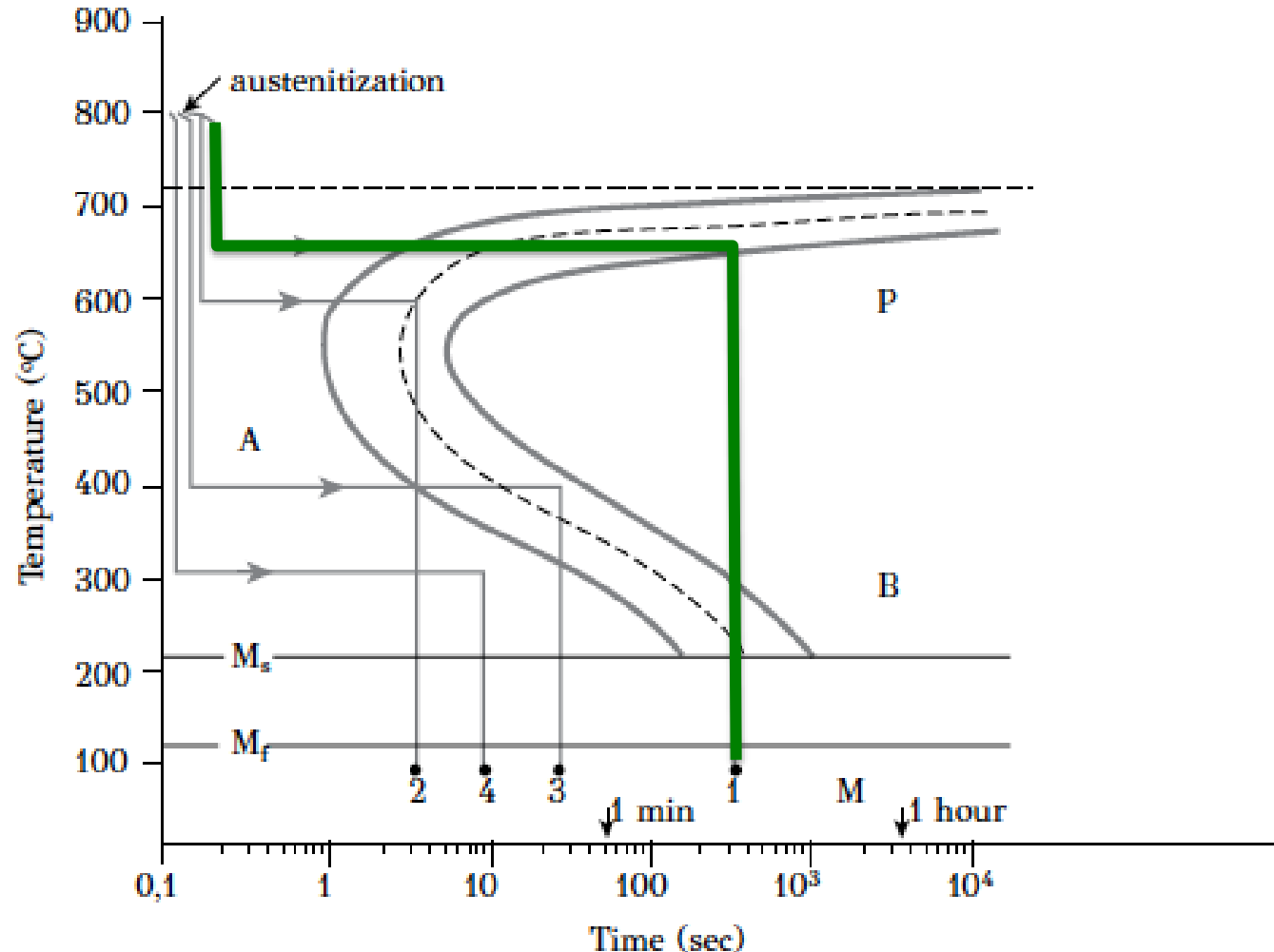# IT diagram – structure development
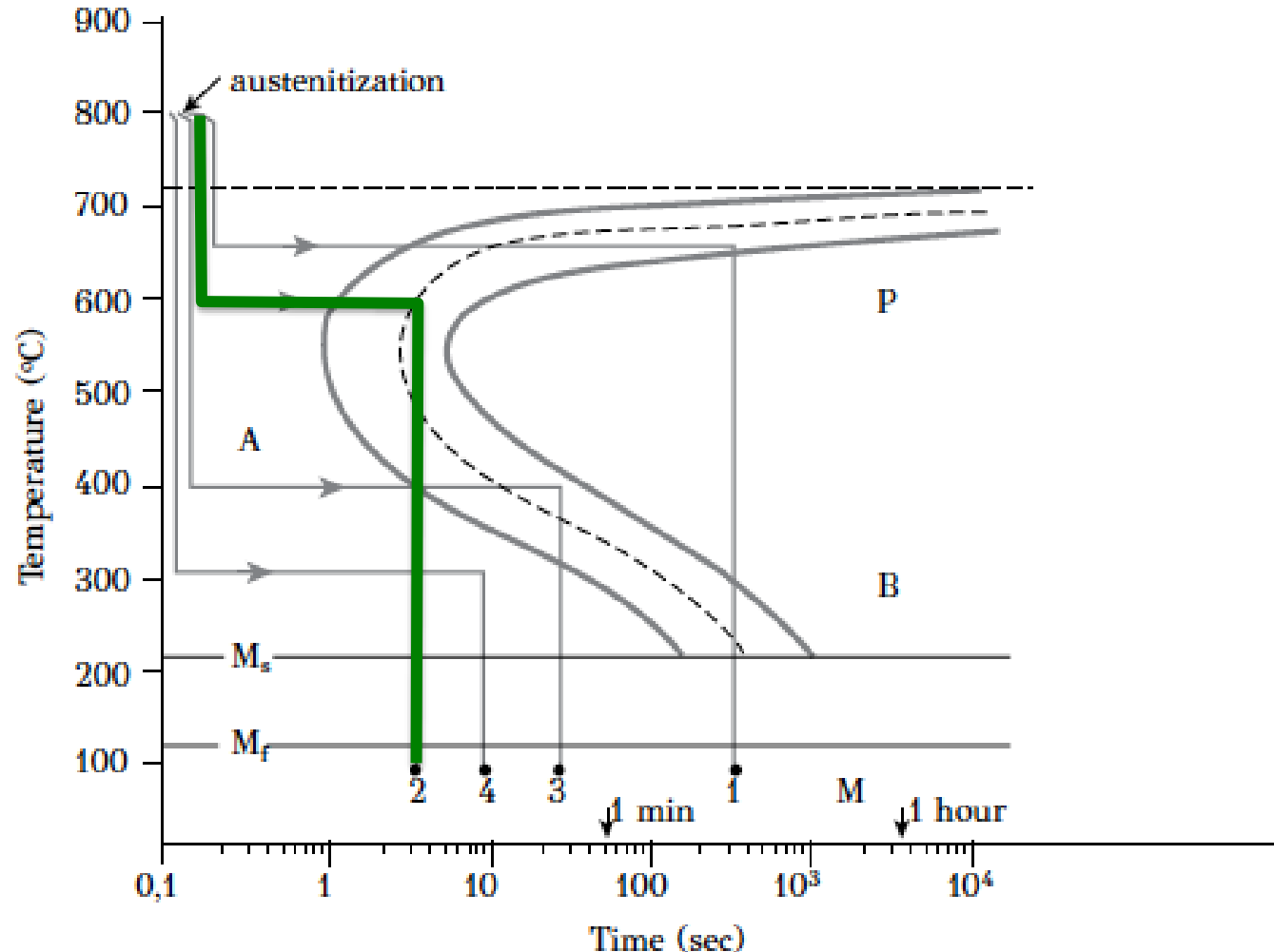

Schematic study of the structure development when transformation is not allowed to complete

Isothermal transformation diagram

Line 1

➢ Cooled to 650 °C, held for 300 sec., then quenched to room temperature

➢ Austenite transformation proceeds to 90% pearlite

➢ During qunching the remaining 10% austenite transforms to martensite

➢ The final microstructure is 90% pearlite – 10% martensite
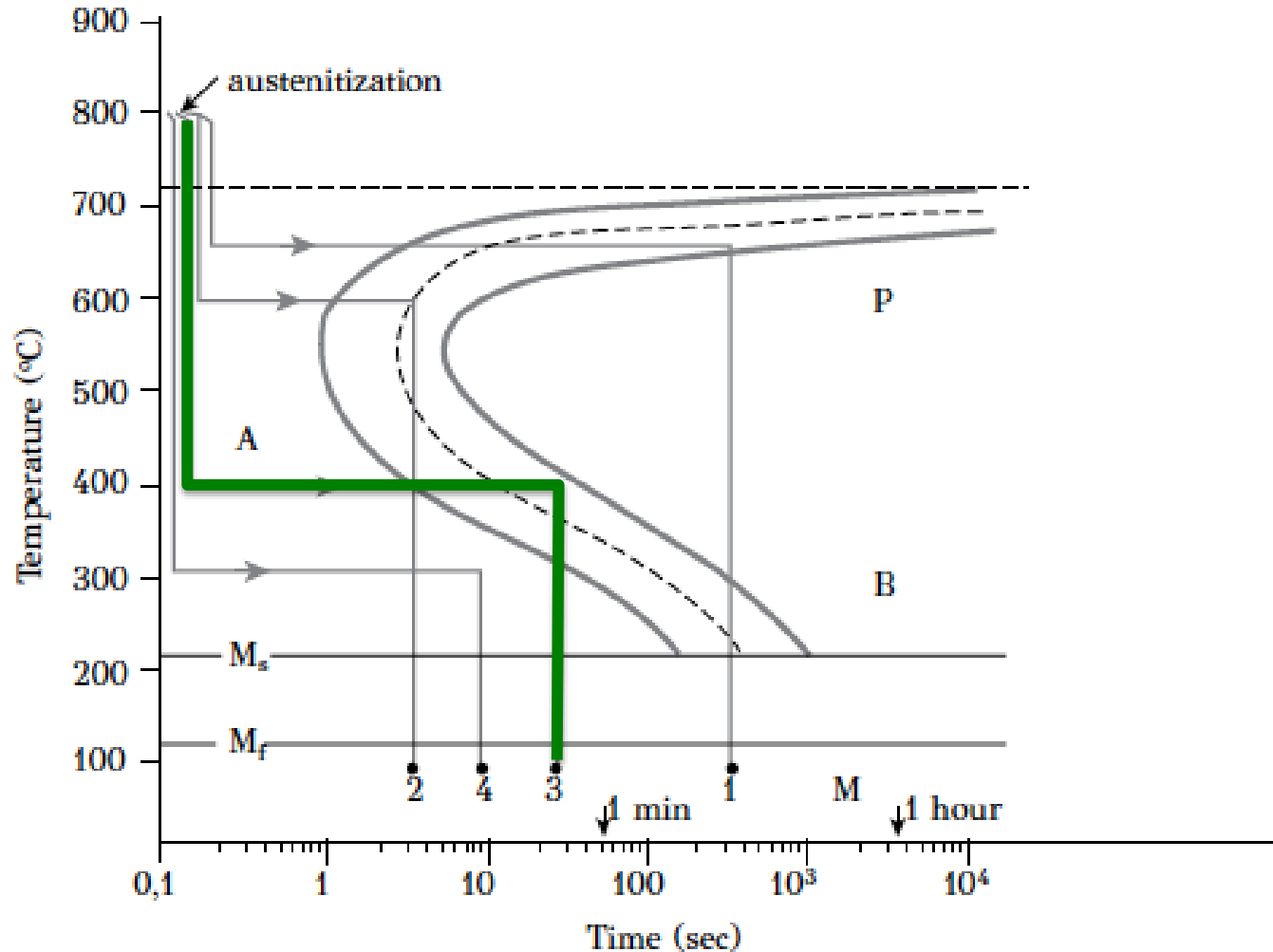
IT diagram – structure development

Schematic study of the structure development when transformation is not allowed to complete

Isothermal transformation diagram

Line 2

➢ Cooled to 600 °C, held for 3 sec., then quenched to room temperature

➢ Austenite transformation proceeds to 50% pearlite

➢ During qunching the remaining 50% austenite transforms to martensite

➢ The final microstructure is 50% pearlite – 50% martensite

# IT diagram – structure development

Schematic study of the structure development when transformation is not allowed to complete

Isothermal transformation diagram

Line 3

➢ Cooled to 400 °C, held for 30 sec., then quenched to room temperature

➢ Austenite transformation proceeds to 80% bainite

➢ During qunching the remaining 20% austenite transforms to martensite

➢ The final microstructure is 80% bainite – 20% martensite

Effect on steel properties
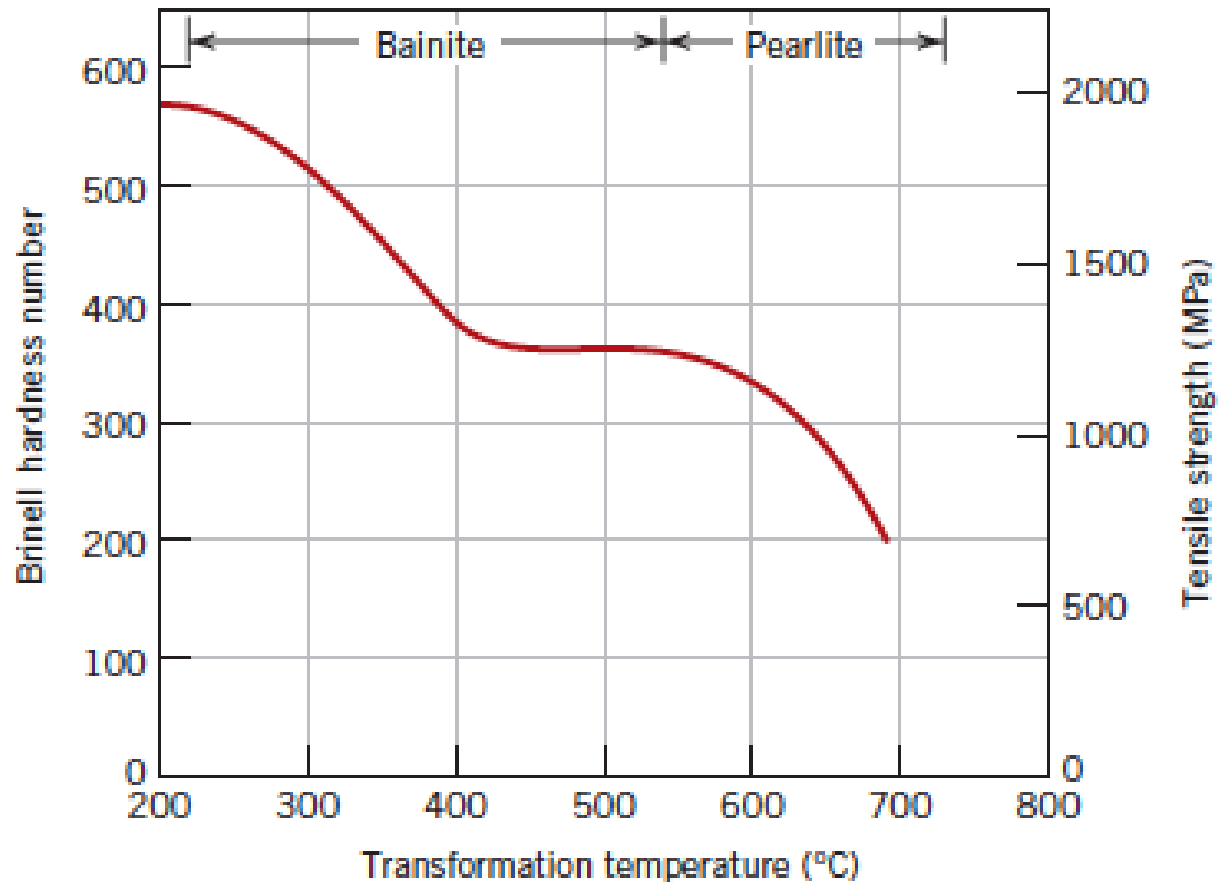
Effect of isothermal transformation temperature on mechanical properties of eutectoid steel
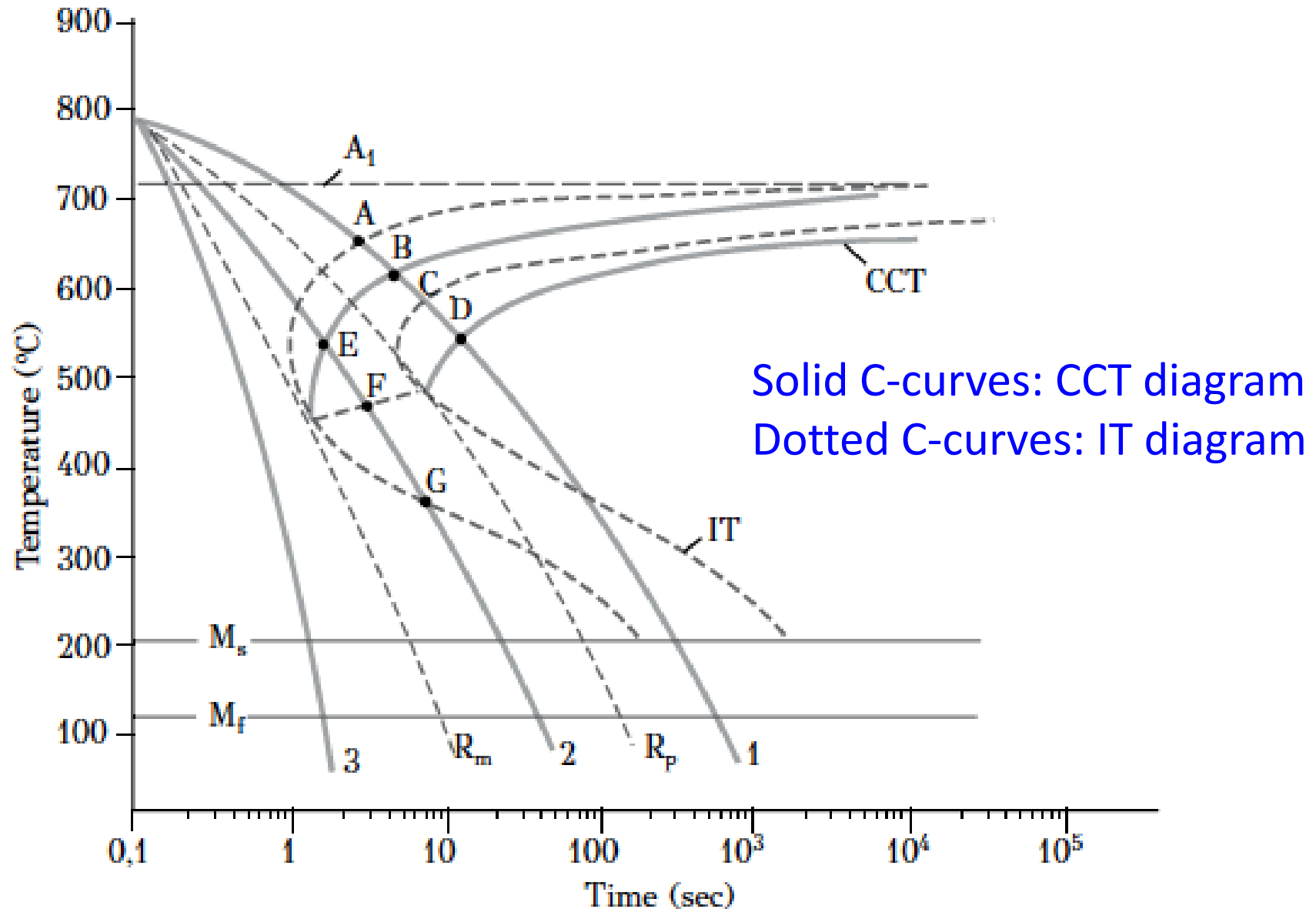
Continuous Cooling Transformation (CCT) diagram

➢ In the vast majority of real world applications, the transformation of austenite occurs under continuous cooling

➢ In such situations, CCT diagram is used in place of IT diagram

➢ There are certain differences between IT and CCT diagrams

Lecture 3

IT & CCT diagrams - differences

Solid C-curves: CCT diagram
Dotted C-curves: IT diagram

IT & CCT diagrams - differences

➢ For continuous cooling, the time required for a reaction to begin and end is delayed. Hence, the C-curves for continuous cooling are shifted to longer times and lower temperatures

➢ For continuous cooling, no bainite will be formed. This is due to the fact that, by the time bainite starts to form, all the austenite has already transformed to pearlite. Thus CCT curves of plain carbon steels do not predict bainite formation.

CCT diagram – critical temperatures
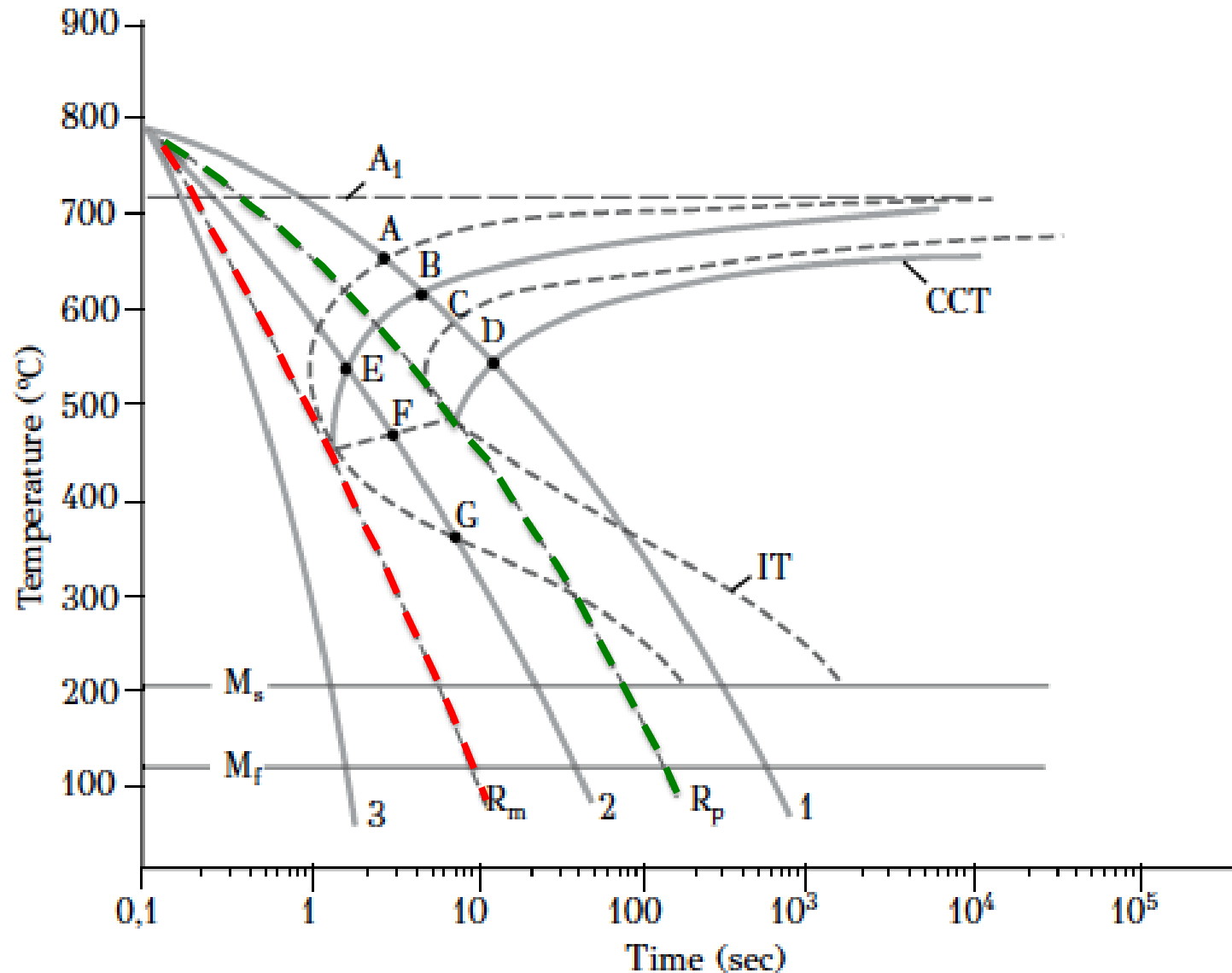
CCT diagram – critical temperatures

Two critical cooling rates are marked in the CCT diagram

Critical cooling rate R_p, marked by the green line

This denotes the fastest cooling rate to obtain 100% pearlite. Any cooling rate slower than this cooling rate will result into full pearlite.

Critical cooling rate R_m, marked by the red line

This denotes the slowest cooling rate to obtain 100% martensite. To obtain a fully martensitic structure, the cooling rate needs to be faster than this.
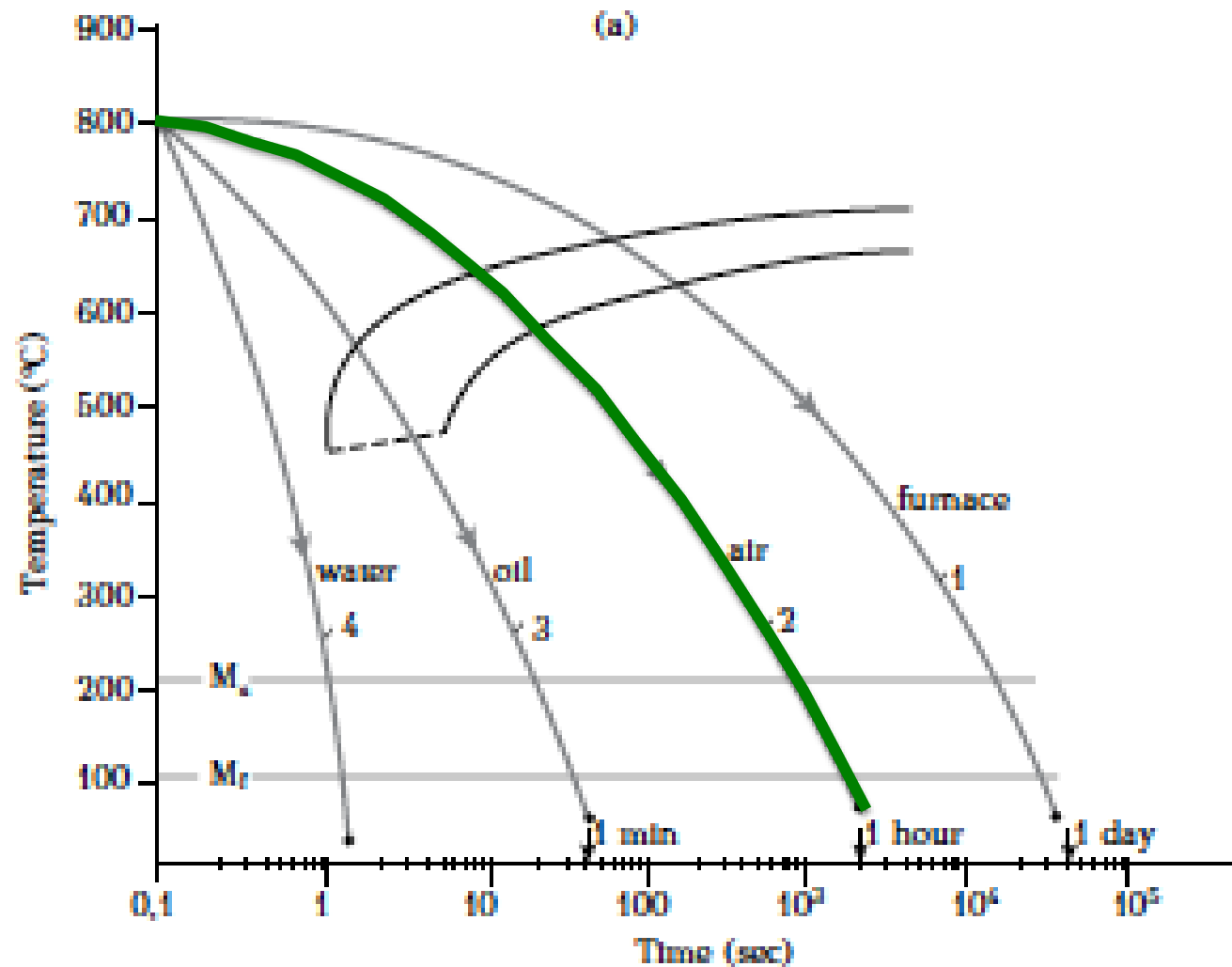
CCT diagram – structure development
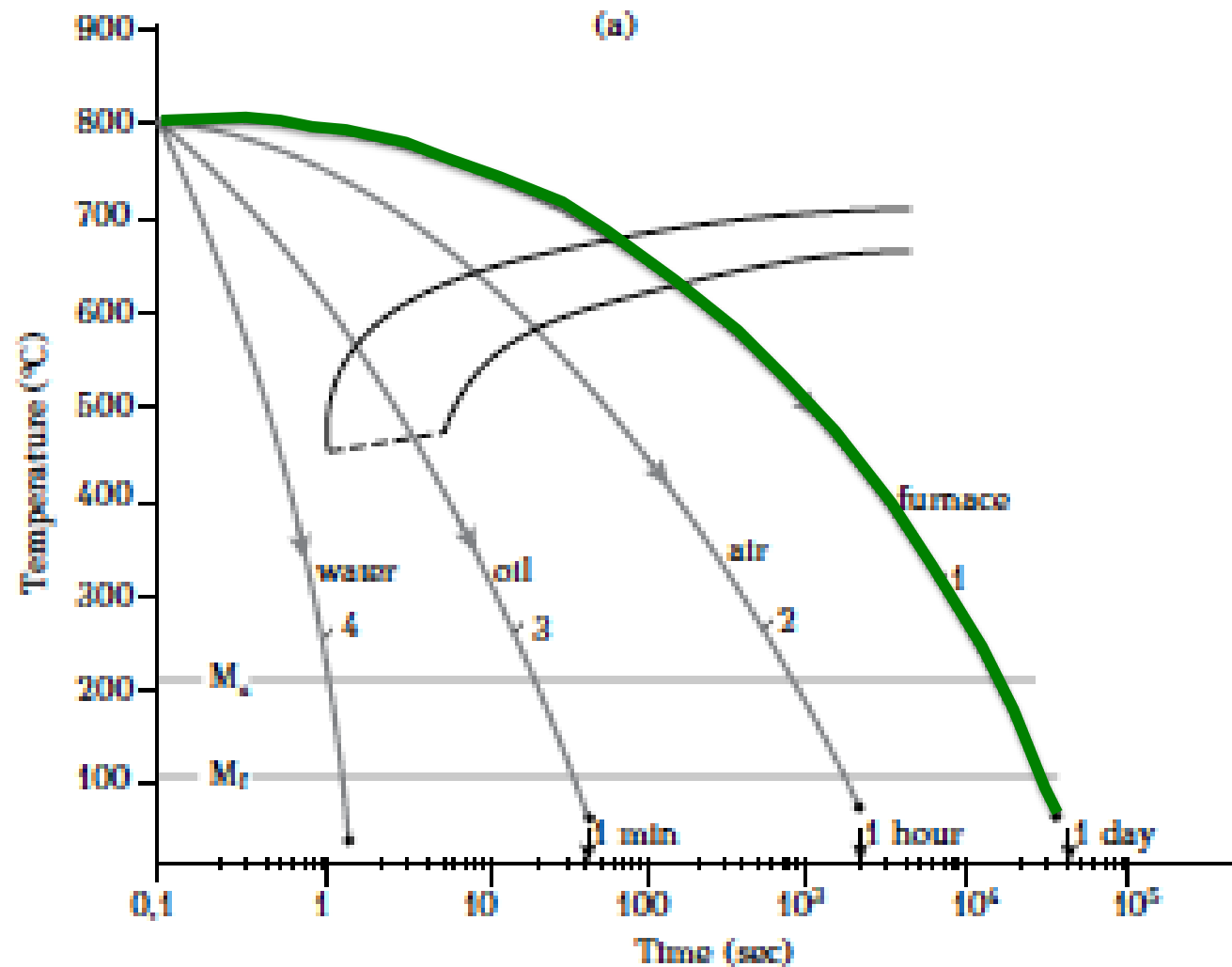
CCT diagram – structure development

➤ Specimen 1 is cooled very slowly inside a furnace

➤ It takes 1 day to cool from 800 °C to room temperature

➤ The cooling curve crosses both the transformation curves at relatively high temperatures (cooling rate slower than R_p discussed earlier)

➤ The microstructure will be completely pearlitic and due to the high transformation temperature, the pearlite will be coarse

➤ The steel will be soft and have a high ductility
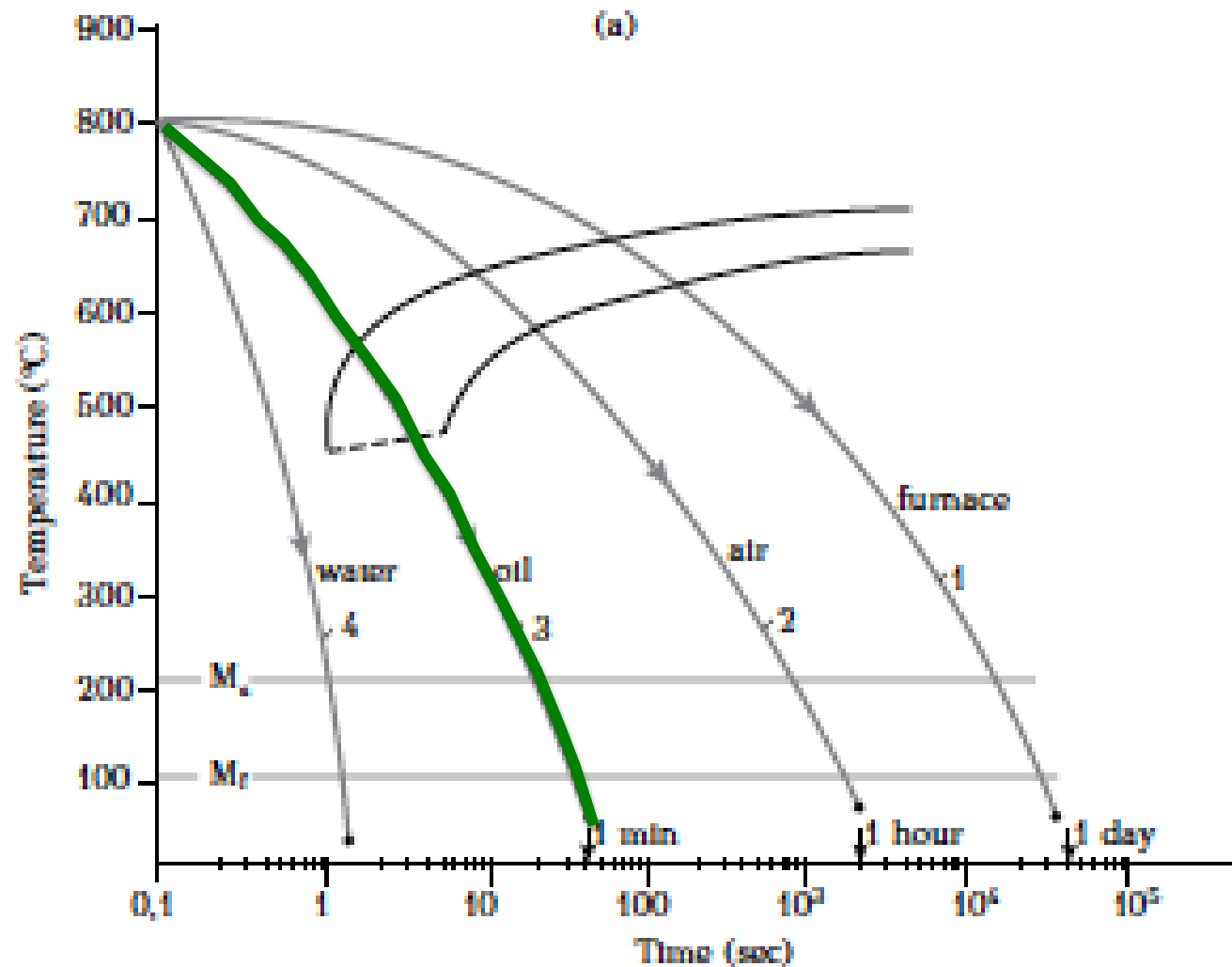
CCT diagram – structure development

CCT diagram – structure development

➢ Specimen 2 is cooled relatively slowly in air

➢ It takes 1 hour to cool from 800 °C to room temperature

➢ The cooling curve crosses both the transformation curves at lower temperatures (cooling rate slower than R_p discussed earlier)

➢ The microstructure will be completely pearlitic and due to the lower transformation temperature, the pearlite will be fine

➢ The steel will be harder than sample 1 and have a lower ductility

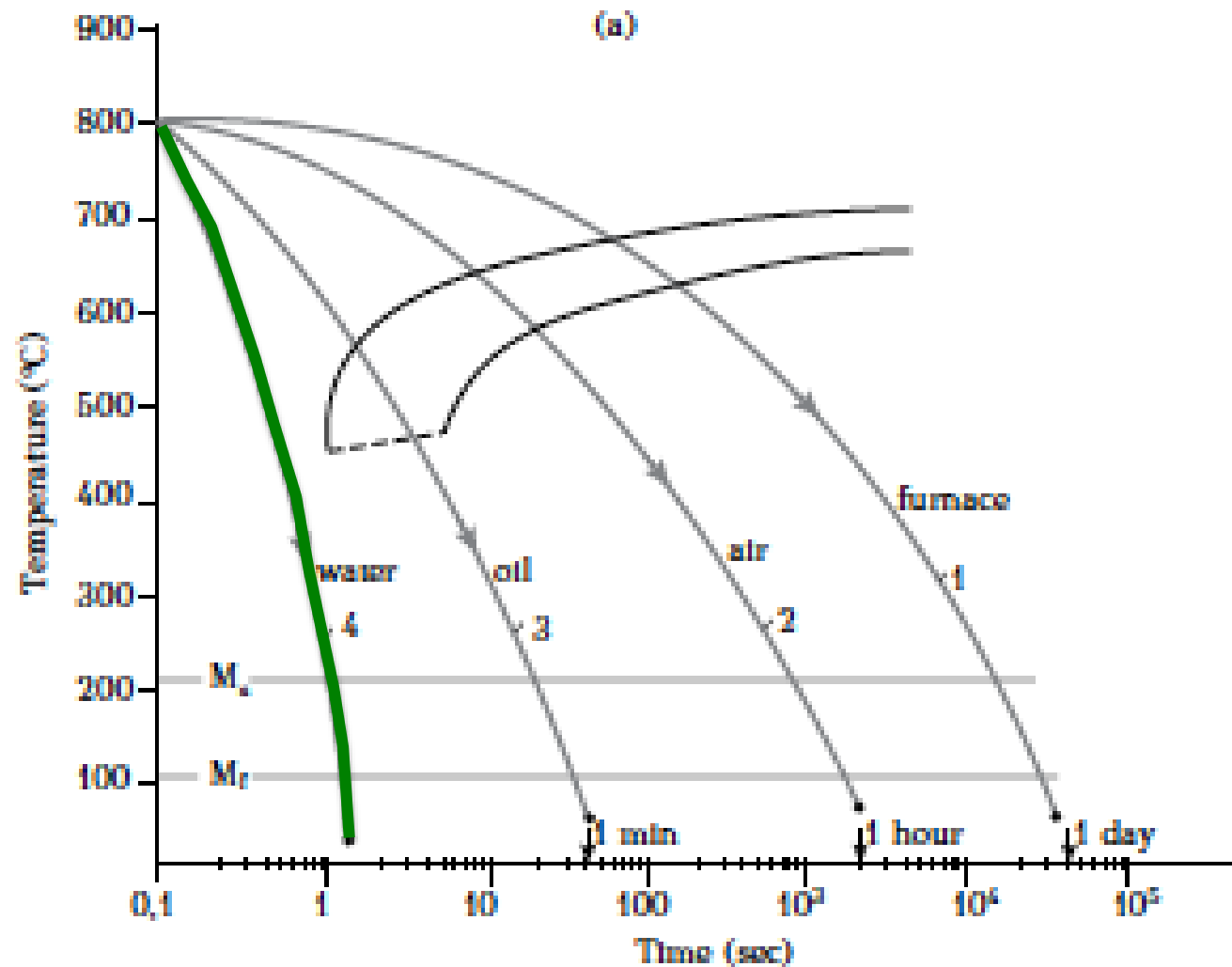# CCT diagram – structure development

(a)

CCT diagram – structure development

➢ Specimen 3 is cooled rather fast by quenching in oil

➢ It takes 1 minute to cool from 800 °C to room temperature

➢ The cooling curve crosses only the start transformation curve (cooling rate intermediate between R_m and R_p discussed earlier)

➢ Austenite will only partly transform to pearlite. Rest of the untransformed austenite will form martensite ➔ final microstructure will be a mixture of fine pearlite and martensite

➢ The steel will be hard and its ductility will be limited

CCT diagram – structure development

CCT diagram – structure development

➢ Specimen 4 is cooled very fast by quenching in water

➢ It is cooled instantly from 800 °C to room temperature

➢ The cooling curve crosses none of the transformation curves (cooling rate faster than R_m)

➢ Austenite will completely convert to martensite

➢ The steel will be extremely hard and very brittle

Tempering of martensite

➢ In the as quenched state martensite is extremely hard and brittle and steel in this state can hardly be used

➢ Further, due to the very fast cooling, the component may have high residual stresses

➢ The heat treatment employed to enhance the ductility and toughness of martensite and reduce the internal stresses in martensite is called tempering

➢ Tempering is performed by heating the martensitic steel between 250 – 650 °C and holding for a certain period.

Tempering of martensite

➤ During tempering the supersaturated BCT martensite transforms to tempered martensite consisting of ferrite and cementite

➤ The cementite in tempered martensite is dispersed as fine particles within the ferrite matrix.

➤ Tempered martensite can be almost as hard and strong as martensite, but with much improved ductility and toughness

➤ The finer the cementite in tempered martensite ➔ the higher will be the hardness and strength

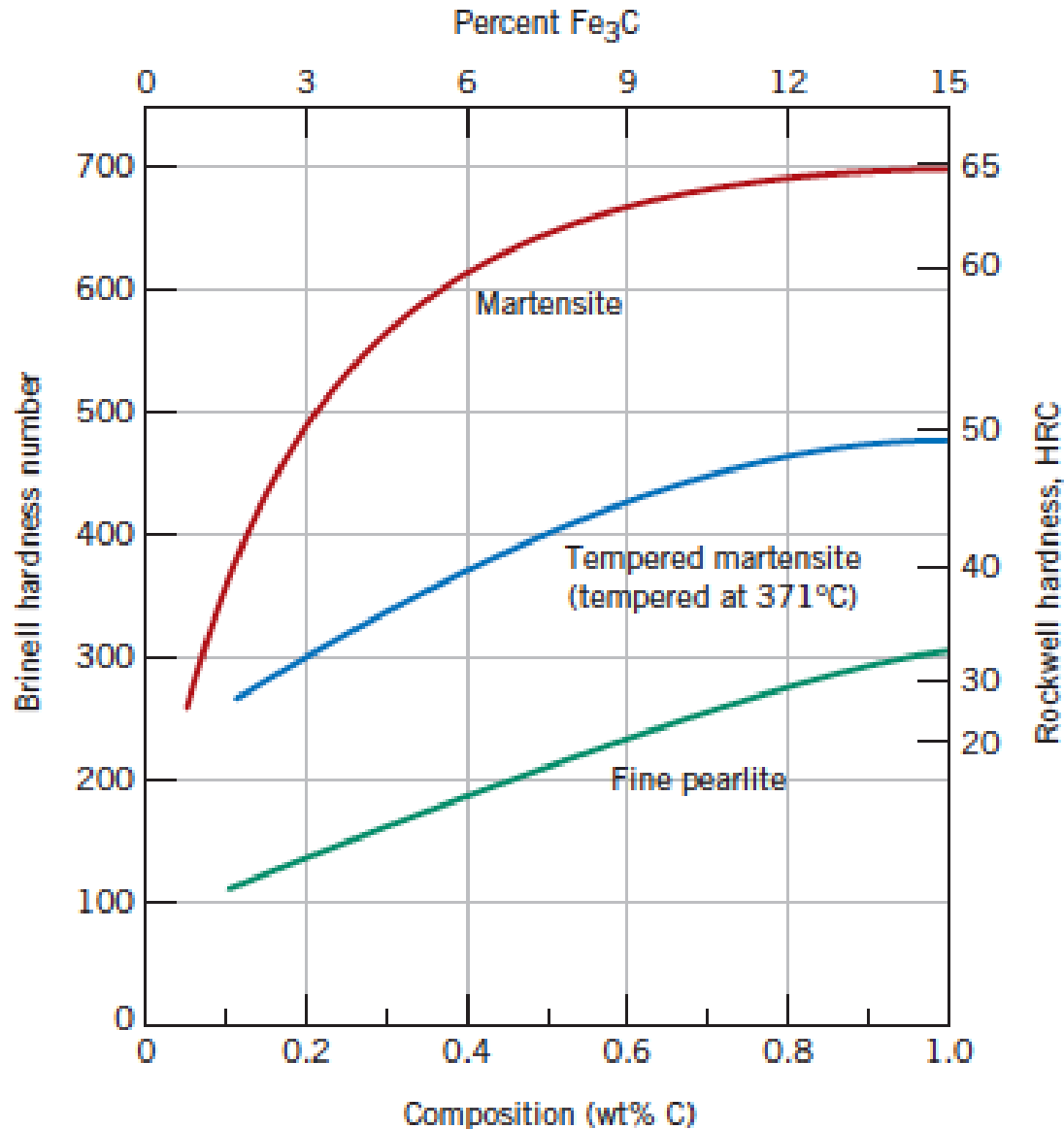➤ With ⬆ tempering temperature (or time), the strength and hardness ⬇ and ductility ⬆

Tempering of martensite
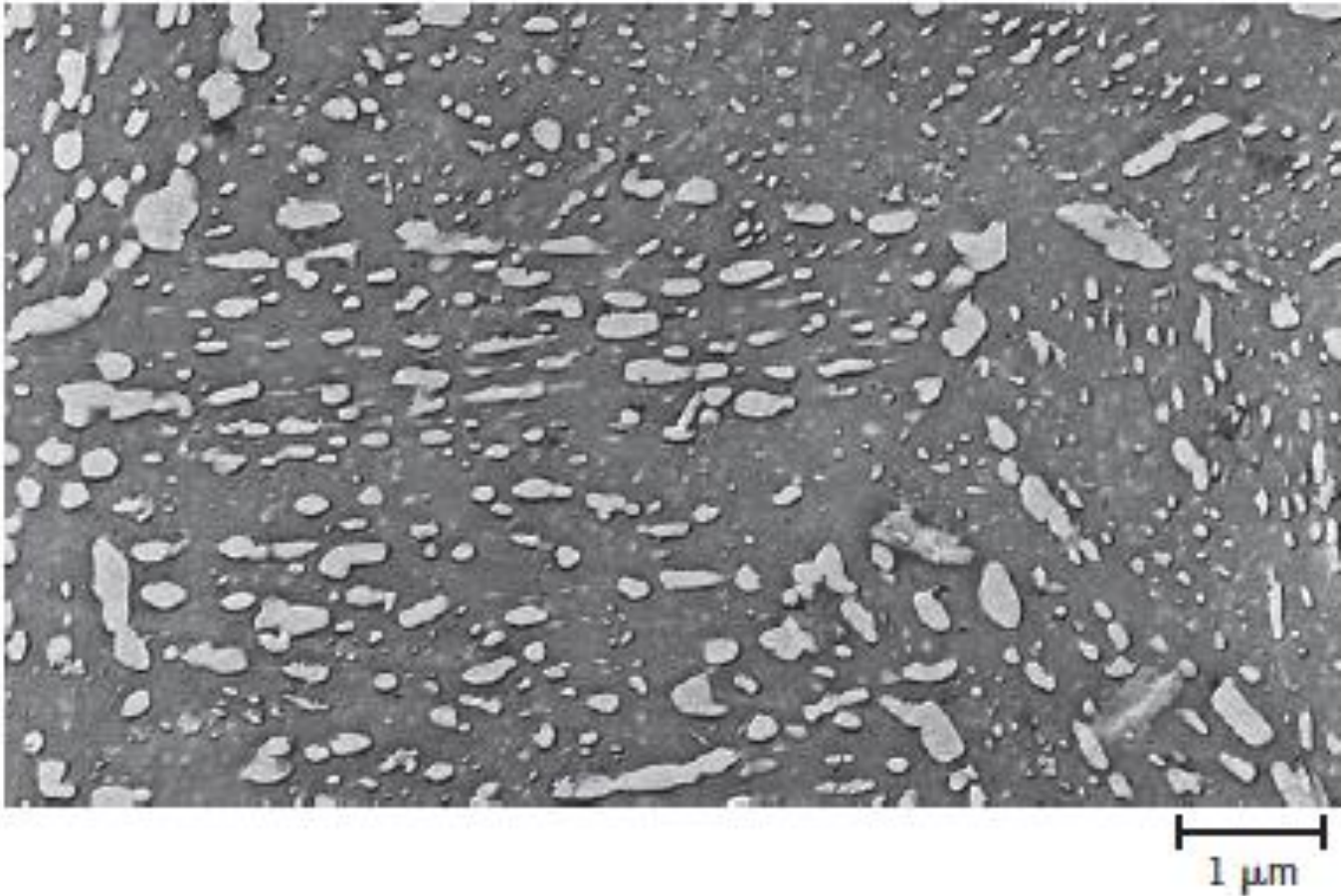
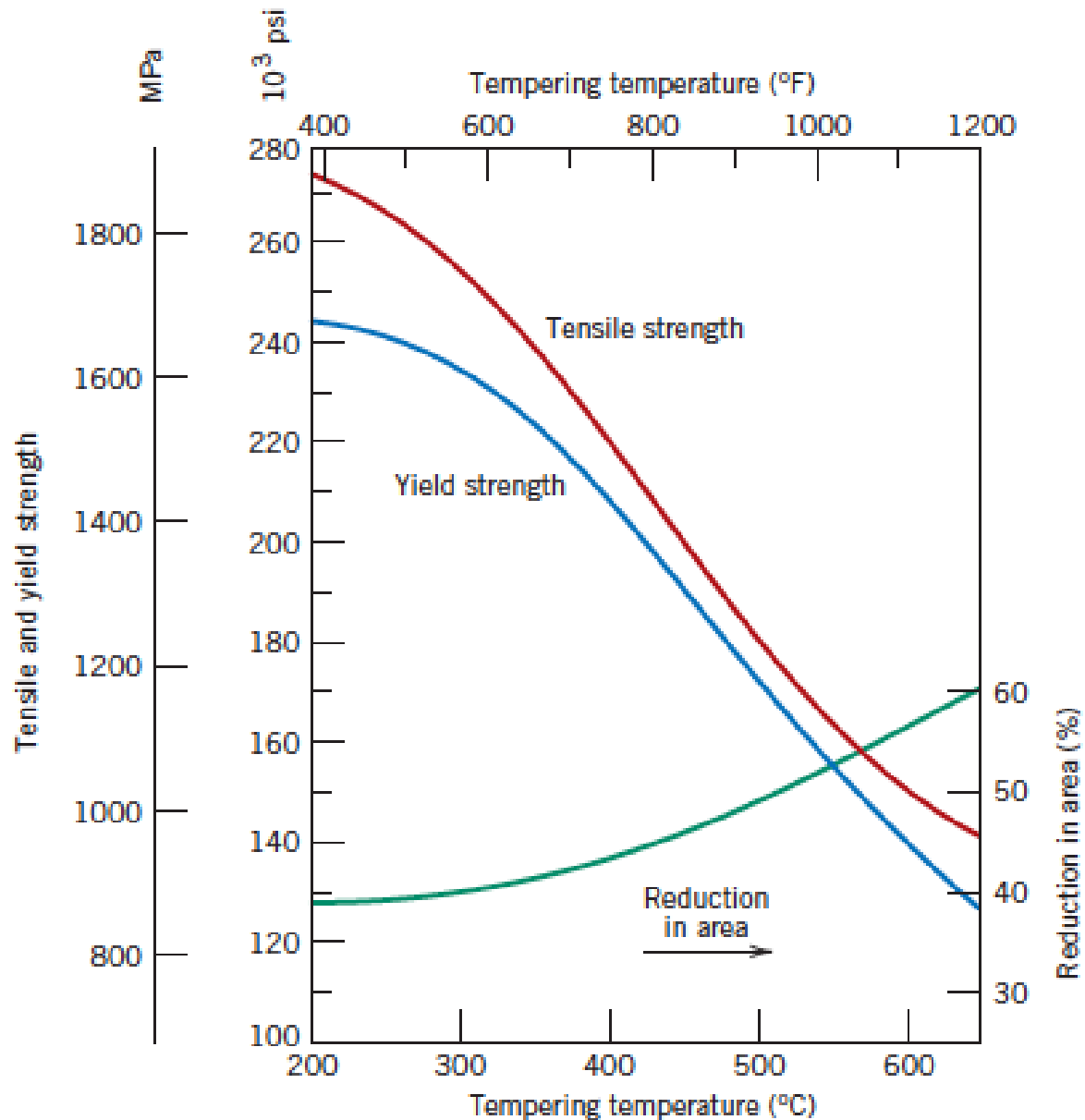Electron micrograph of tempered martensite
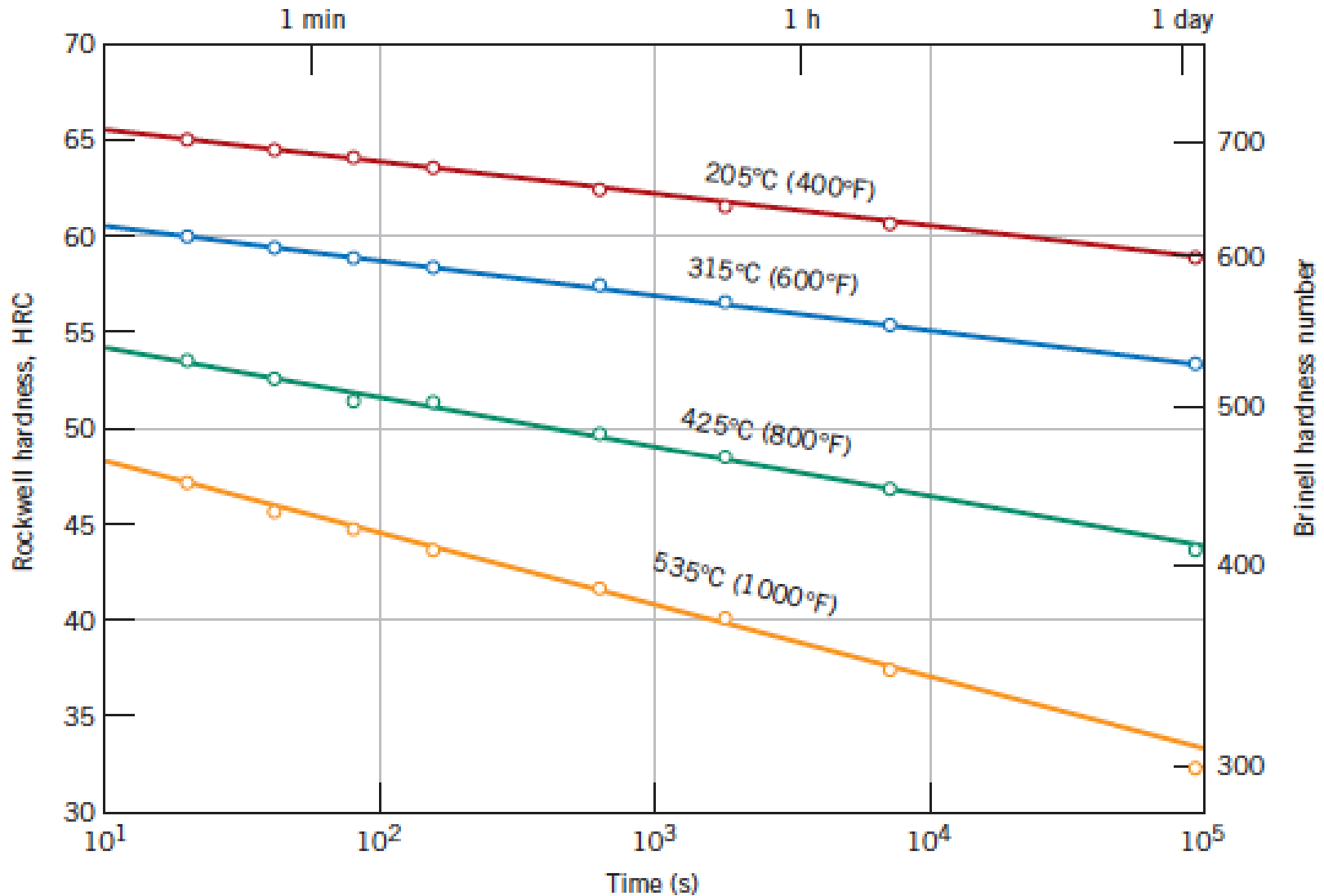
Effect of microstructure on hardness

- Hardness of steel continuously increases with increasing C-content
- At all compositions, martensite has the highest hardness. Hardness of tempered martensite is intermediate to pearlite and martensite
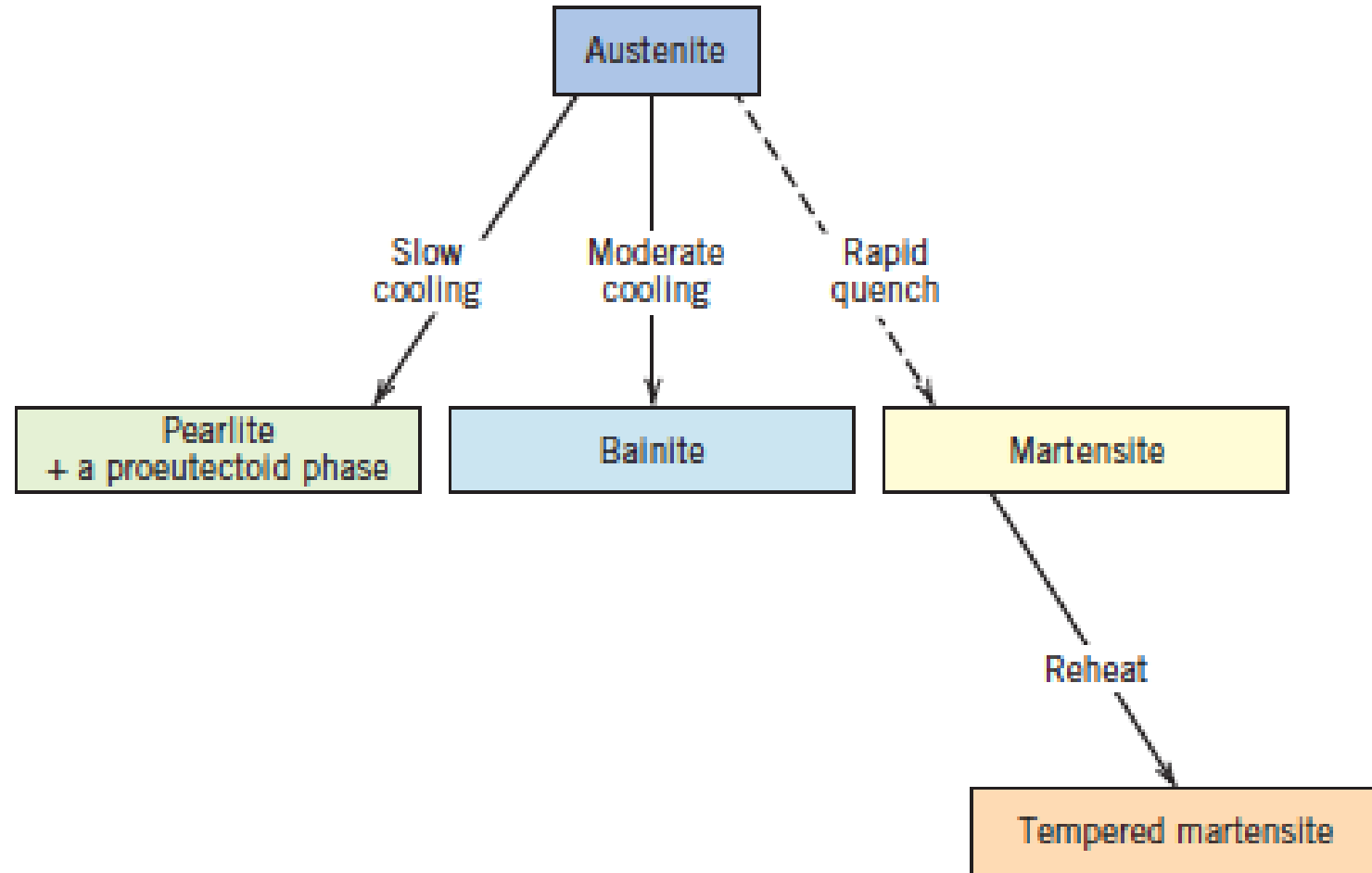
Effect of tempering temperature

Effect of tempering temperature & time

Summary – possible transformations

Summary – possible transformations

Microconstituent	Phases Present	Arrangement of Phases	Mechanical Properties (Relative)
Coarse pearlite	α-Ferrite + Fe$_3$C	Alternating layers of α-ferrite and Fe$_3$C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α-Ferrite + Fe$_3$C	Alternating layers of α-ferrite and Fe$_3$C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α-Ferrite + Fe$_3$C	Very fine and elongated particles of Fe$_3$C in an α-ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered martensite	α-Ferrite + Fe$_3$C	Very small Fe$_3$C 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

Alloying elements in steel

The alloying elements can influence the Fe-Fe$_3$C phase diagram in two broad ways:

➢ By expanding the γ-field and encouraging the formation of austenite over wider compositional limits. These elements are called γ-stabilizer.

➢ By contracting the γ-field and encoraging the formation of ferrite over wider compositional limits. These elements are called α-stabilizer.

Metastable Fe-Fe$_3$C phase diagram
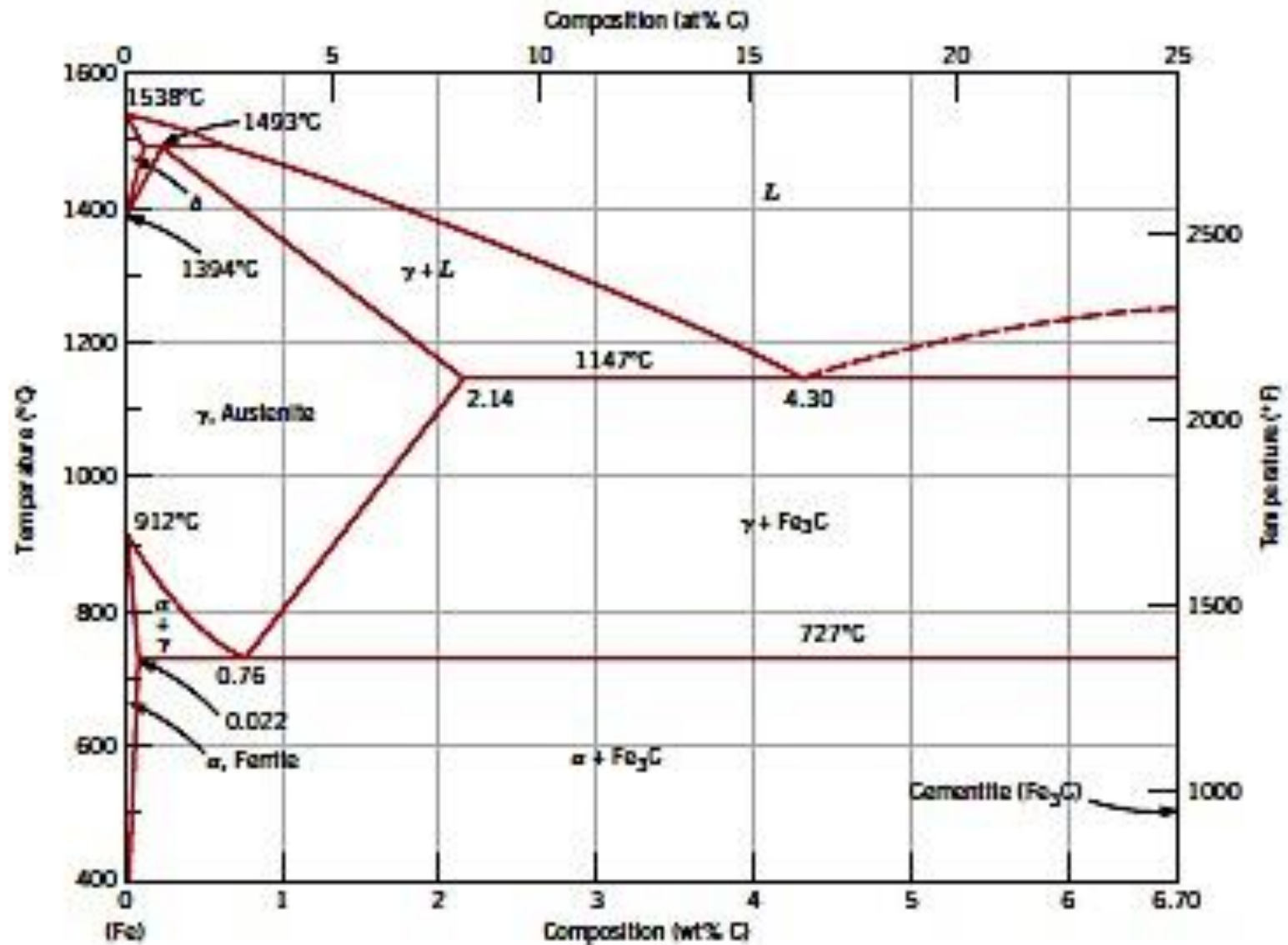
Alloying elements in steel

γ-stabilizers

➢ The alloying elements Ni, Mn as well as Co widen the temperature range for stable austenite by depressing the γ-α transformation and raising the γ-δ transformation.

➢ Ni and Mn lower both A_{c1} and A_{c3} and in sufficient quantities they can completely eliminate the ferrite phase even at room temperature.

➢ The alloying elements C and N expand the γ-field. However its range of existence is cut short by compound formation.
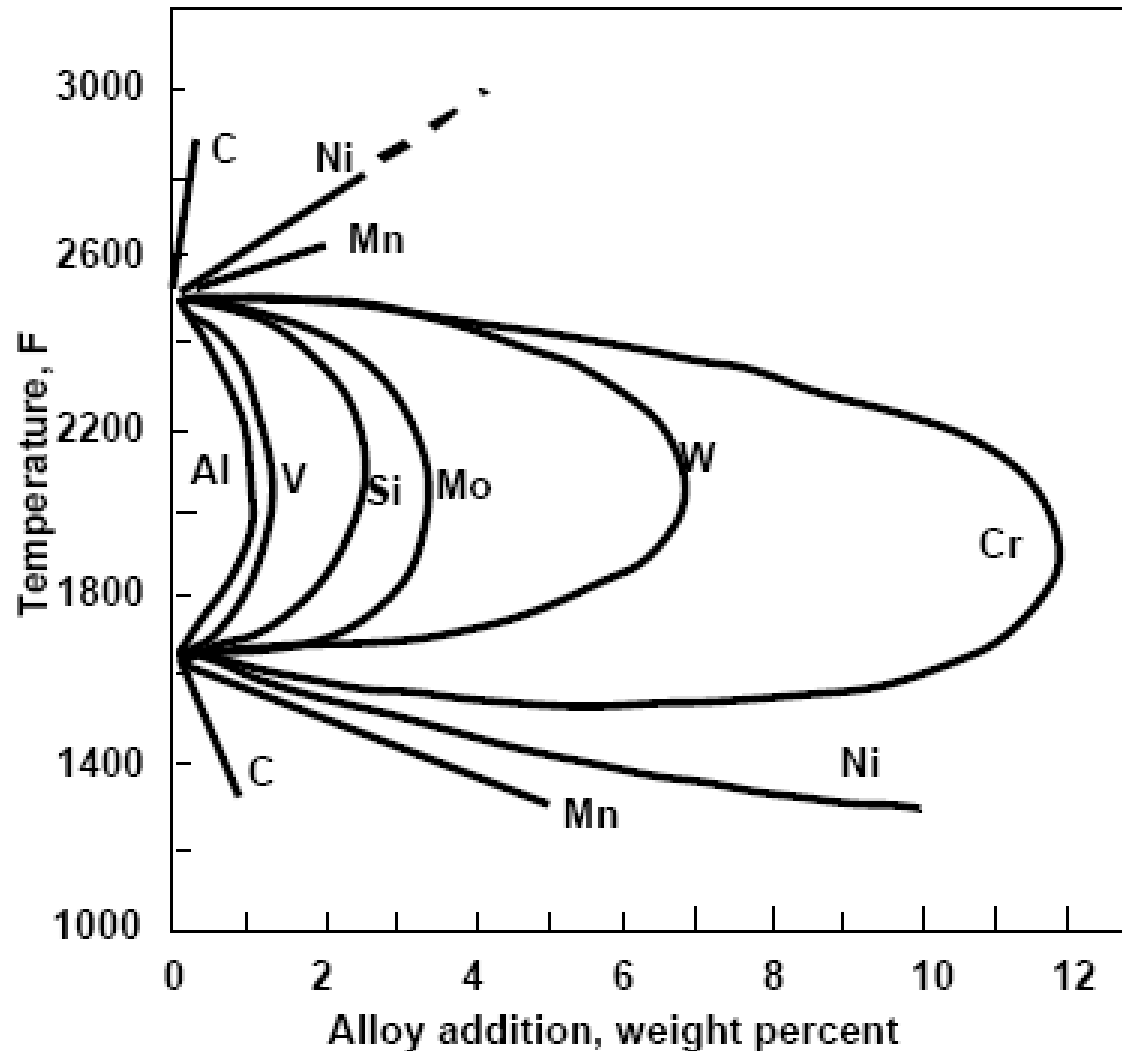
Alloying elements in steel

α-stabilizers

➢ The alloying elements Si, Al, Be, P as well as the strong carbide formers Ti, V, Mo and Cr restrict the formation of γ-phase , causing the formation of a γ-loop.

➢ These elements favor the formation of α-iron and one result is that the δ- and α-phase fields become continuous.

➢ Some elements like B strongly favor compound formation, thereby contracting the γ-loop.

Alloying elements in steel

γ-loop formation in various binary steels

Alloying elements in steel

➢ The crystal structure of solid solutions of iron at room temperature is the important basis for classifying steels

➢ If at room temperature, austenite is the predominant phase due to the addition of sufficient amount of Ni or Mn, the steel is called austenitic steel. E.g.

Hadfield steel – 13% Mn, 1.2% Cr, 1% C

Austenitic stainless steel – 18% Cr, 8% Ni

➢ if the room-temperature structure consists mostly of iron solid solution that is made possible by the ferrite-forming elements, it is called ferritic steel. E.g.

Ferritic stainless steel – Cr content > 13%

Low carbon transformer steel – Si content 3%

Alloying elements in steel

Effect on the eutectoid point

Austenite and ferrite stabilizers affect the eutectoid point differently.

Austenite stabilizers lower the eutectoid temperature, thereby widening the temperature range of austenite

Ferrite formers raise the eutectoid temperature, thereby widening the temperature range of ferrite
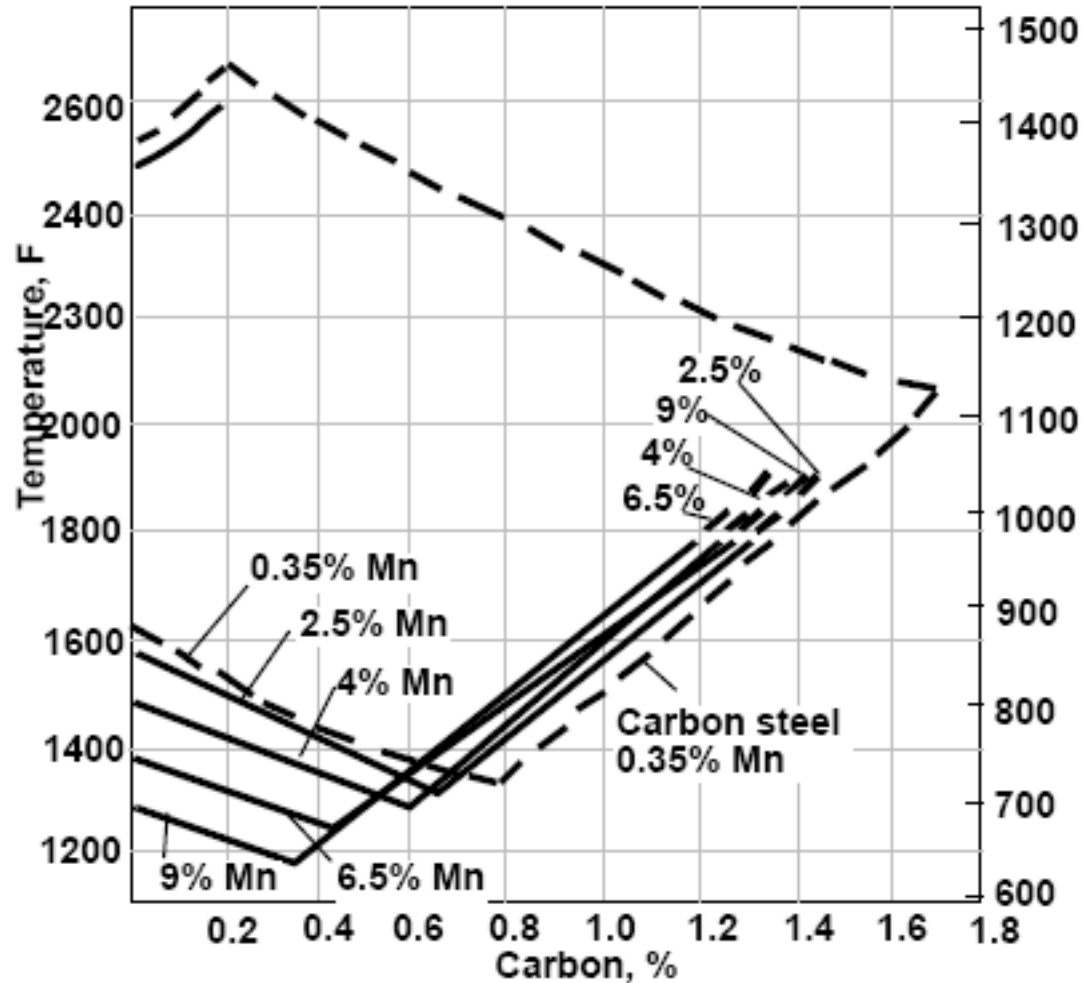
Alloying elements in steel

Effect on the eutectoid temperature
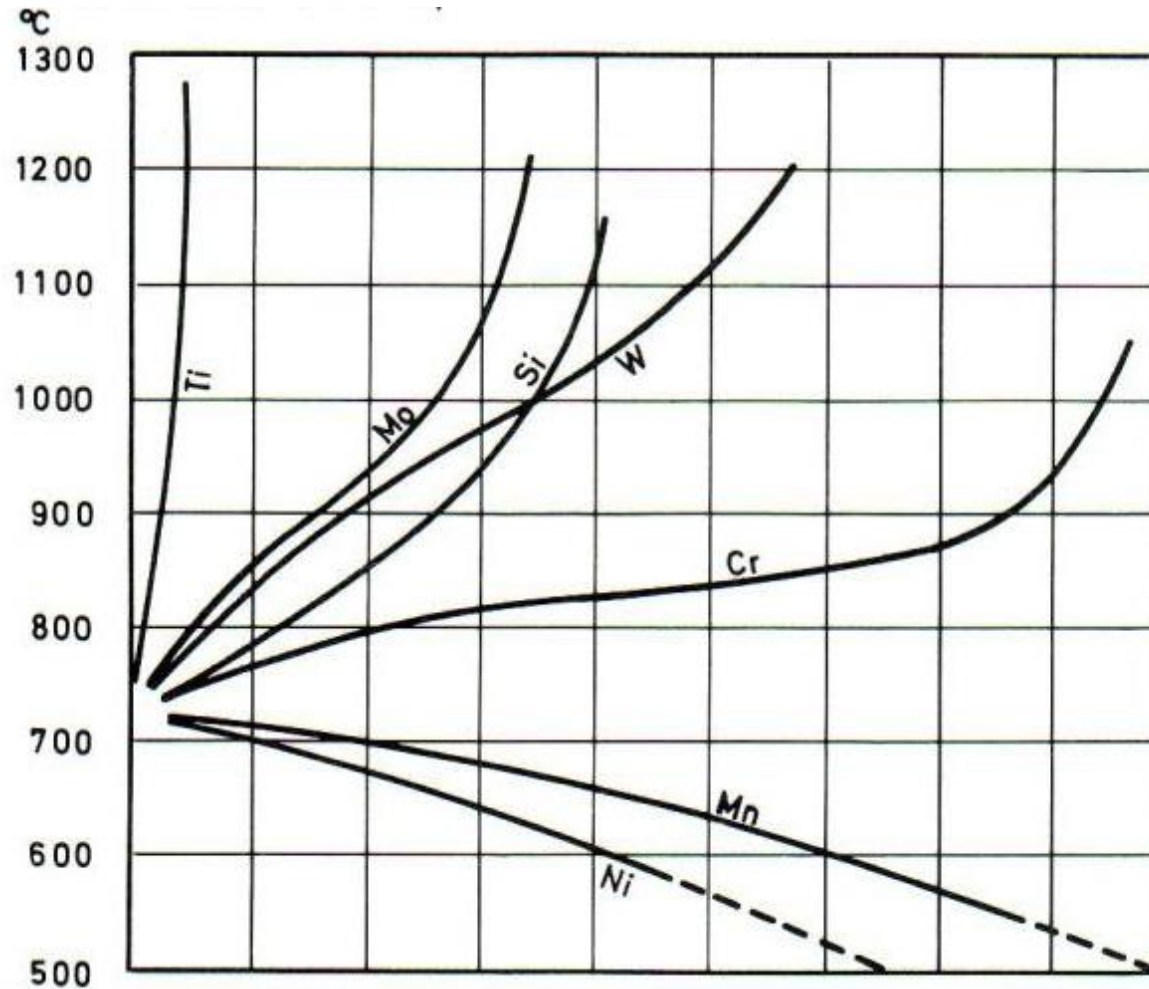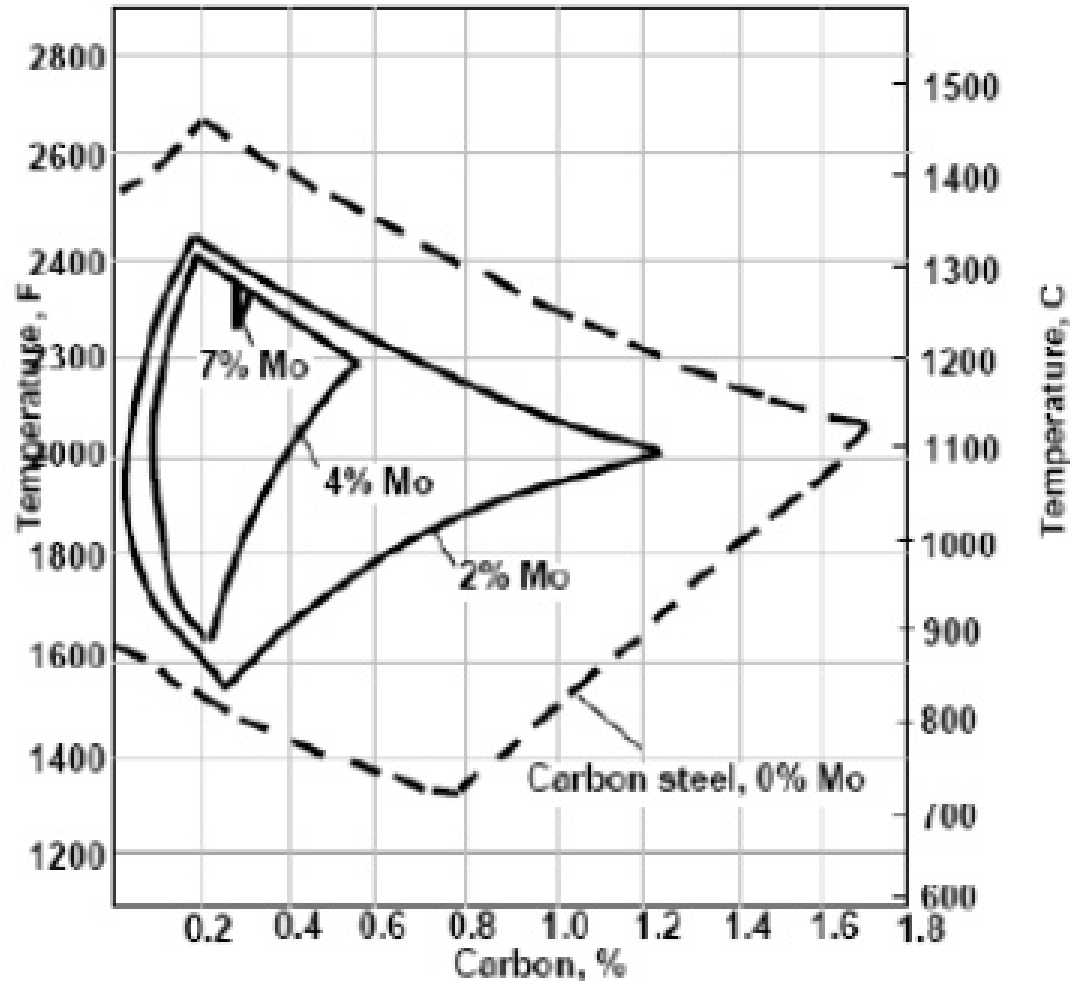
Alloying elements in steel

Effect of alloying element on γ-field

Effect of Mn, an austenite stabilizer

Alloying elements in steel

Effect of alloying element on γ-field

Effect of Mo, a ferrite stabilizer

Alloying elements in steel

Distribution of alloying elements

In terms of their distribution in steel, alloying elements can be classified into two groups:

i)   Elements that do not form carbides in steel: Ni, Si, Co, Al, Cu, N etc.

ii) Elements that form stable carbides in steel: Cr, Mo, W, V, Ti, Zr, Nb etc.

Alloying elements in steel

Non-carbide forming alloying elements

➢ They are present in steel only as solid solutions with iron

➢ Nitrogen has a very limited solubility in iron

➢ When the N-content is > 0.015%, nitrogen forms stable nitrides with iron or alloying elements like V, Al, Ti, Cr etc.
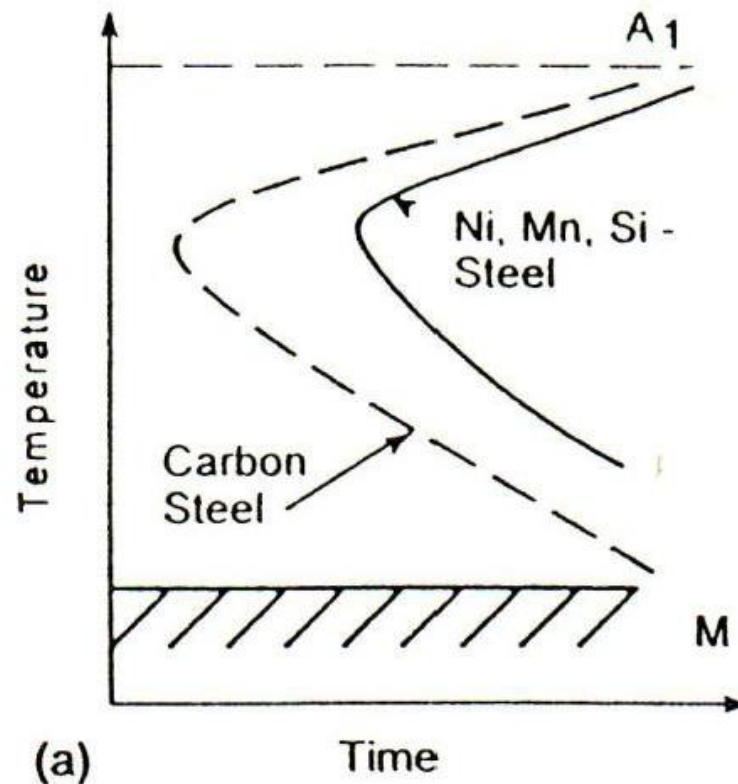
Alloying elements in steel

Carbide forming alloying elements

➢ Carbide forming alloying elements in steel can be found either as stable carbides or as solid solution in iron

➢ The distribution of these elements depends upon the C-content and the amount of these elements

➢ In a steel containing relatively less amount of carbon and large amount of alloying elements, these elements are predominantly present as solid solution in iron

➢ In steels containing large amount of carbon and relatively less amount of alloying elements, these elements are predominantly present as carbides.

Alloying elements in steel

Effect on transformation diagram

Alloying elements that do not form carbides (e.g. Ni, Si, Cu, Al etc.) slow the austenite to pearlite transformation ➜ nose of the C-curve is shifted to larger times.

(a)   Time

Alloying elements in steel

Effect on transformation diagram

Carbide formers (e.g. Cr, Mo, W, V etc.) affect the austenite-pearlite differently at different temperatures:

➢ Within 500 – 700 °C (region of pearlite formation), they slow down the transformation

➢ Within 400 – 500 °C, they dramatically slow down the transformation

➢ Within 300 – 400 °C (region of beinite formation), they speed up the transformation

Alloying elements in steel

Effect on transformation diagram
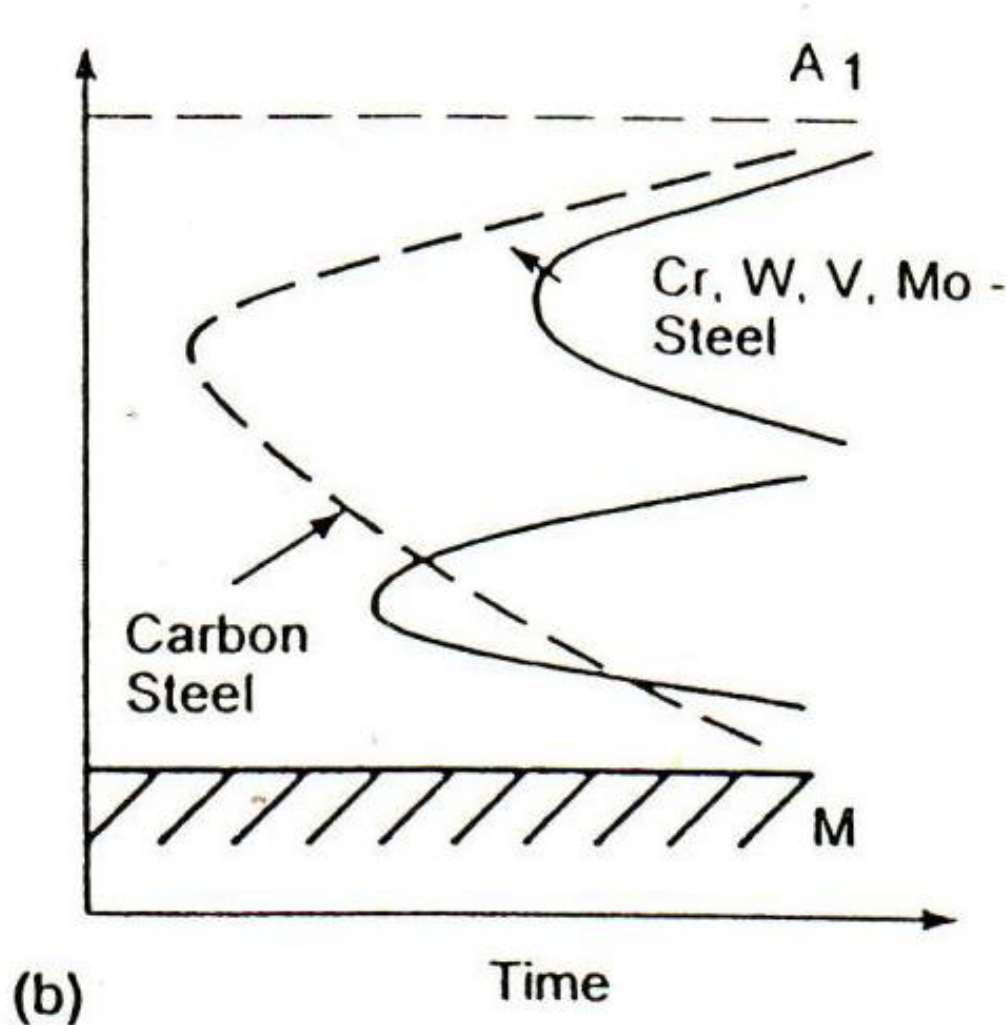
- ➤ Transformation diagram of these allow steels generally have separate curves for pearlite and bainite transformation

- ➤ For these steels, bainite formation is possible under continuos cooling
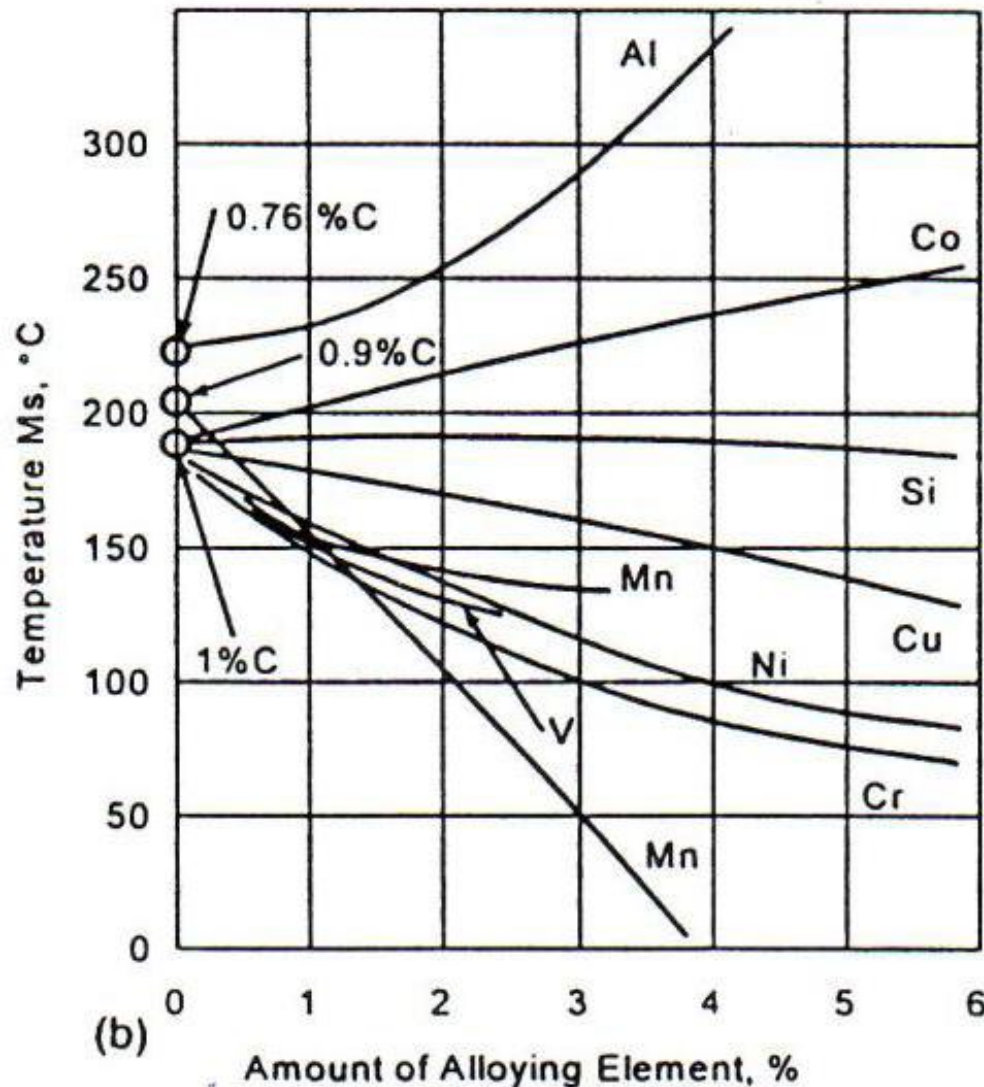
Alloying elements in steel

Effect on M_s and M_f temperatures

➢ Most alloying elements which enter into solid solution of austenite lower the M_s temperature

➢ The interstitial elements C and N have the largest effect

➢ Only Co and Al behave differently ➔ these two elements raise the M_s temperature
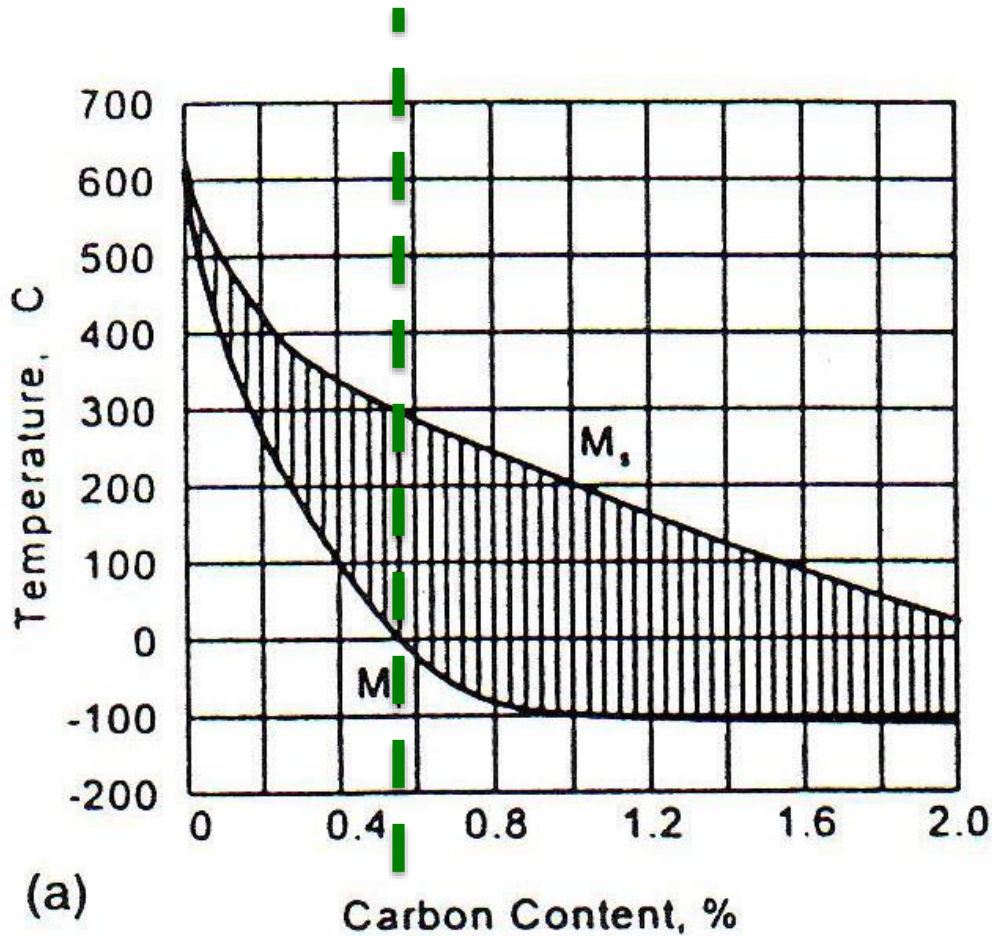
Alloying elements in steel
Effect on M$_s$ and M$_f$ temperatures

Effect of different alloying elements on M$_s$ temperature in a steel with 1% C-content

Alloying elements in steel

Effect on M_s and M_f temperatures

(a)

Effect of C-content on Ms and M_f temperatures

In steels with > 0.5% C the M_f-temperature is below room temperature. Such steels when cooled fast to room temperature will have retained austenite in them.

Alloying elements in steel

Effect on grain growth

➤ The elements Al, V, Nb and Ti in small amounts (between 0.03-0.1 wt.%) strongly inhibit the grain growth of the austenite phase.

➤ The grain refinement in ferritic-pearlitic steels is obtained by restricting the austenite grain growth during hot forming

➤ These elements are present as highly dispersed carbides, nitrides or carbonitrides and they only go into solution at very high temperatures.

➤ These precipitate particles inhibit the growth of austenite grains ➜ finer microstructure

# Alloying elements in steel

Effect on grain growth
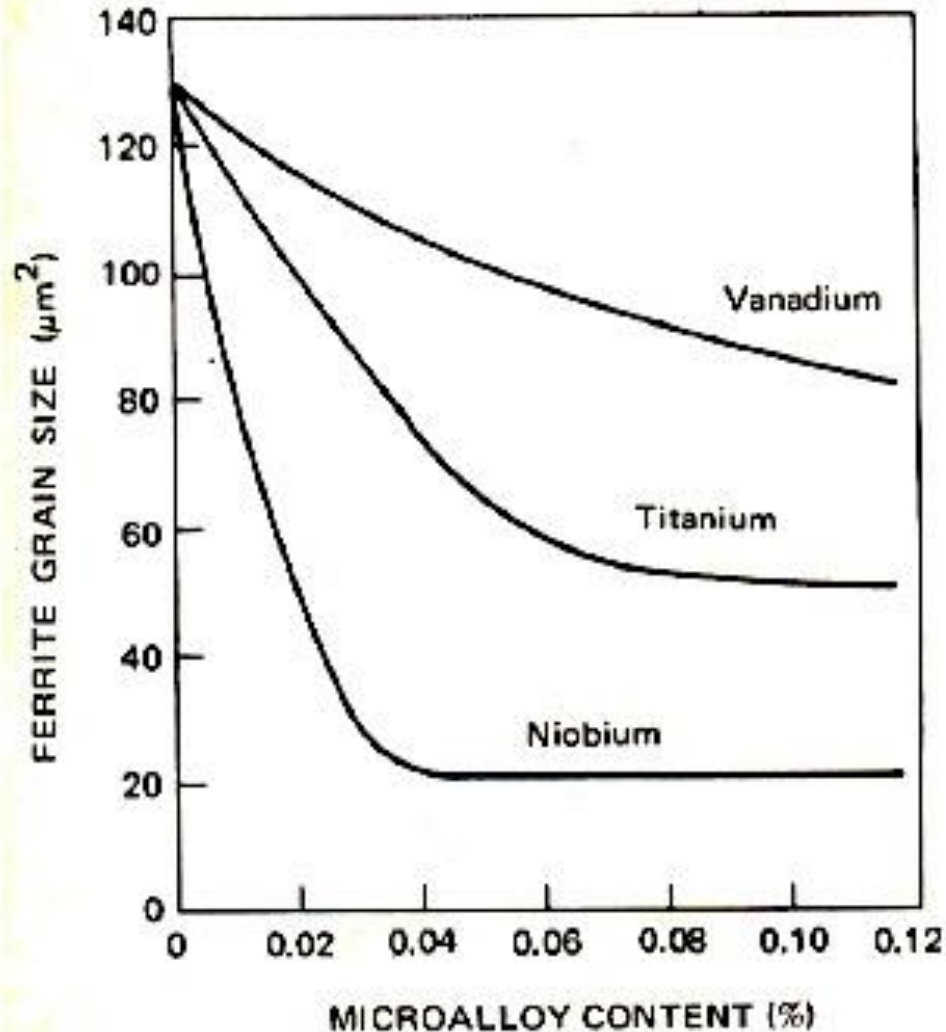
Lecture 4

Hardenability of steel

Hardenability is defined as the ease with which a steel forms martensite.

➢ Steels with higher hardenability form martensite at a lower cooling rate in comparison to those with a lower hardenability.

➢ When quenched in the same medium from the same temperature, a steel with a higher hardenability can form martensite at a larger depth from the surface.
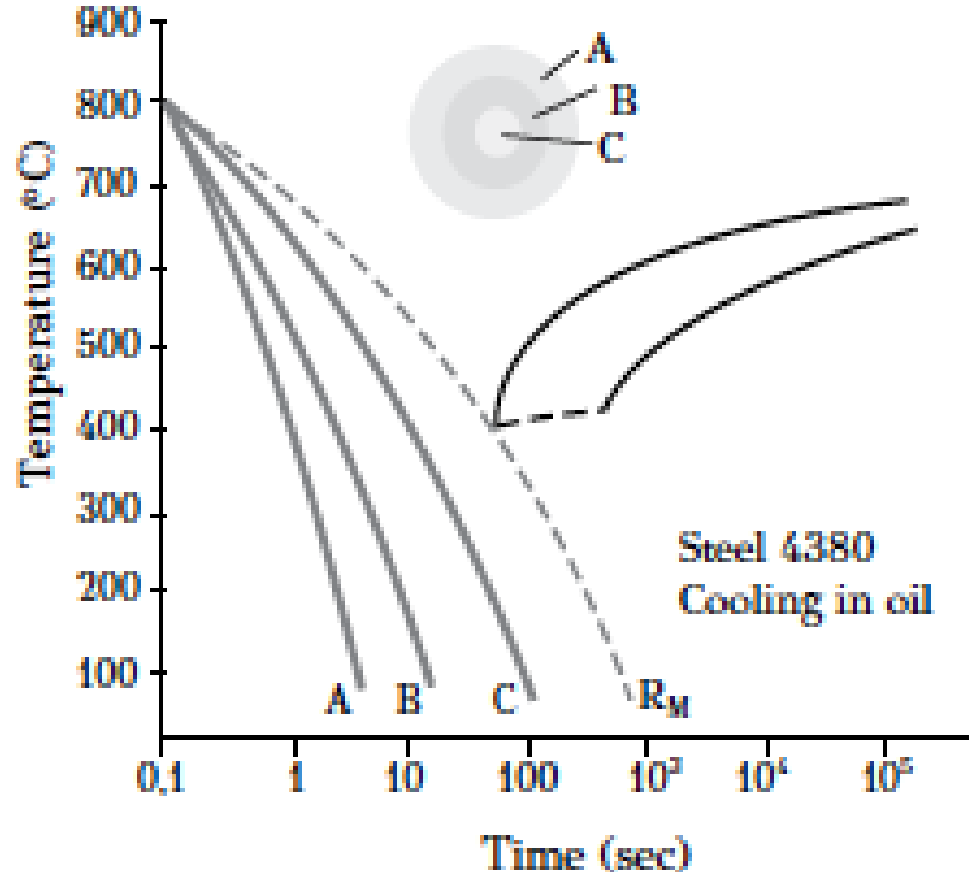
Hardenability of steel
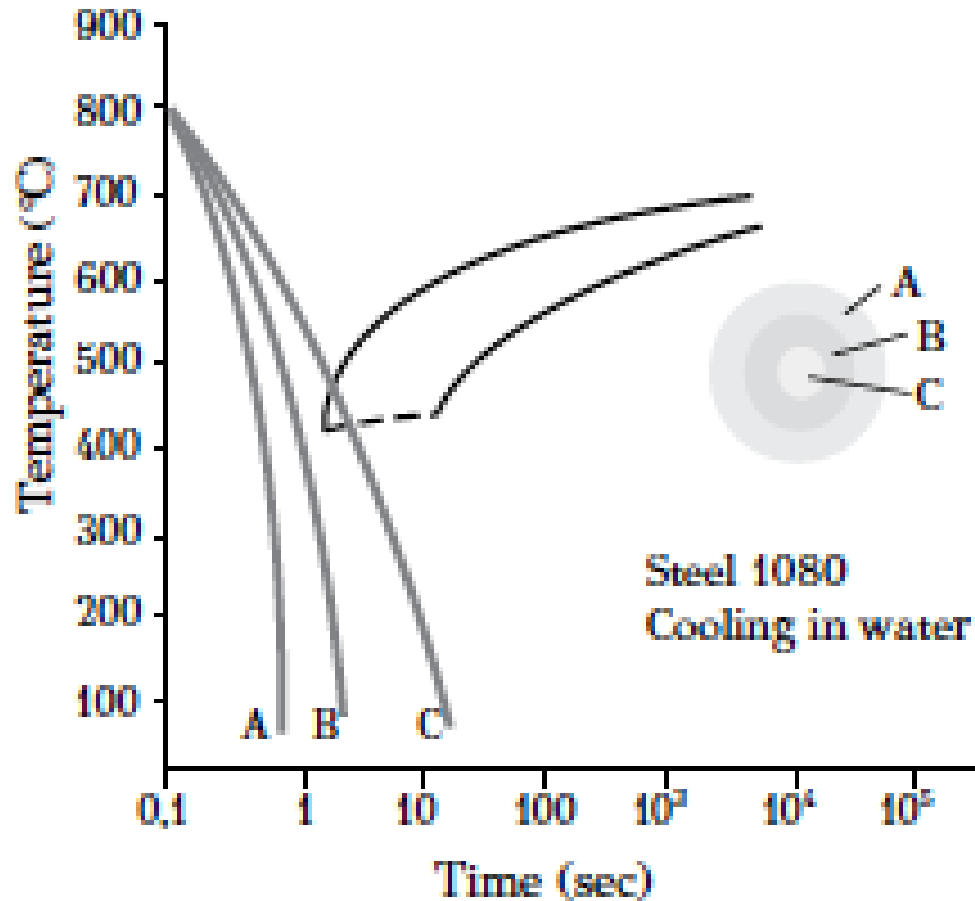
Typical cooling curve for 1080 steel in water

Hardenability of steel

➢ The cooling rates in the regions A and B are faster than the critical cooling rate for martensite formation.

➢ The cooling rate in region C is slower than this critical rate

➢ The steel will not harden thoroughly ➔ hardenability of the steel is low

➢ Using a different medium with a higher cooling rate is a solution. However,

- A too high cooling rate may initiate quench cracks

- A too high cooling rate may also distort the part

A possible solution is to use a steel with higher hardenability

Hardenability of steel

The same 3 cooling curves for Steel 4380 in oil passes the nose ➔ steel with higher hardenability that will produce martensite at all depths

Factors affecting steel hardenability

➢ Hardenability is associated with the position of the pearlitic nose in the CCT diagram.

➢ Any factor which delays the diffusive phase transformations to bainite, ferrite or pearlite will shift the nose to higher times ➔ increase the hardenability.

➢ Two of the most important parameters are:

  – C-content and

  – amount of other alloying elments

  – Prior austenite grain size

Effect of C-content on hardenability

➤ C increases the hardenability by slowing the transformation to ferrite and pearlite.
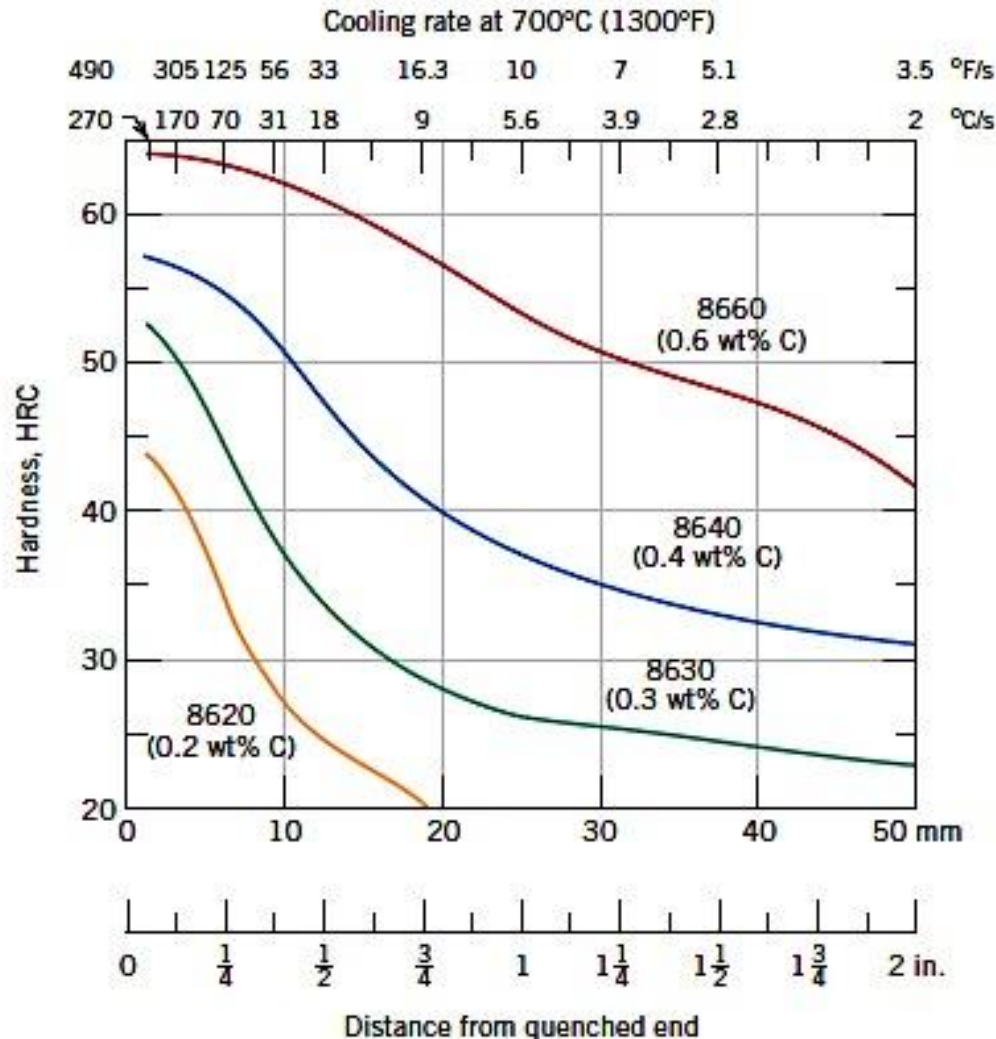
➤ Plot of four alloy steels with different C-content

➤ As the C-content ⬇, the depth of hardness ⬇, i.e. hardenability decreasing with decreasing C-content

Effect of alloying elements

➤ All alloying elements except cobalt enhance the hardenability of steel

➤ Presence of additional alloying elements, irrespective of whether they are ferrite or austenite stabilizers, makes the diffusion controlled transformations to ferrite and pearlite more sluggish.

➤ Correspondingly, the C-curves for transformation shifts to the right and the nose of the pearlitic transformation moves to longer time

➤ Correpondingly, martensite is formed even at slower cooling rates.

Effect of alloying elements
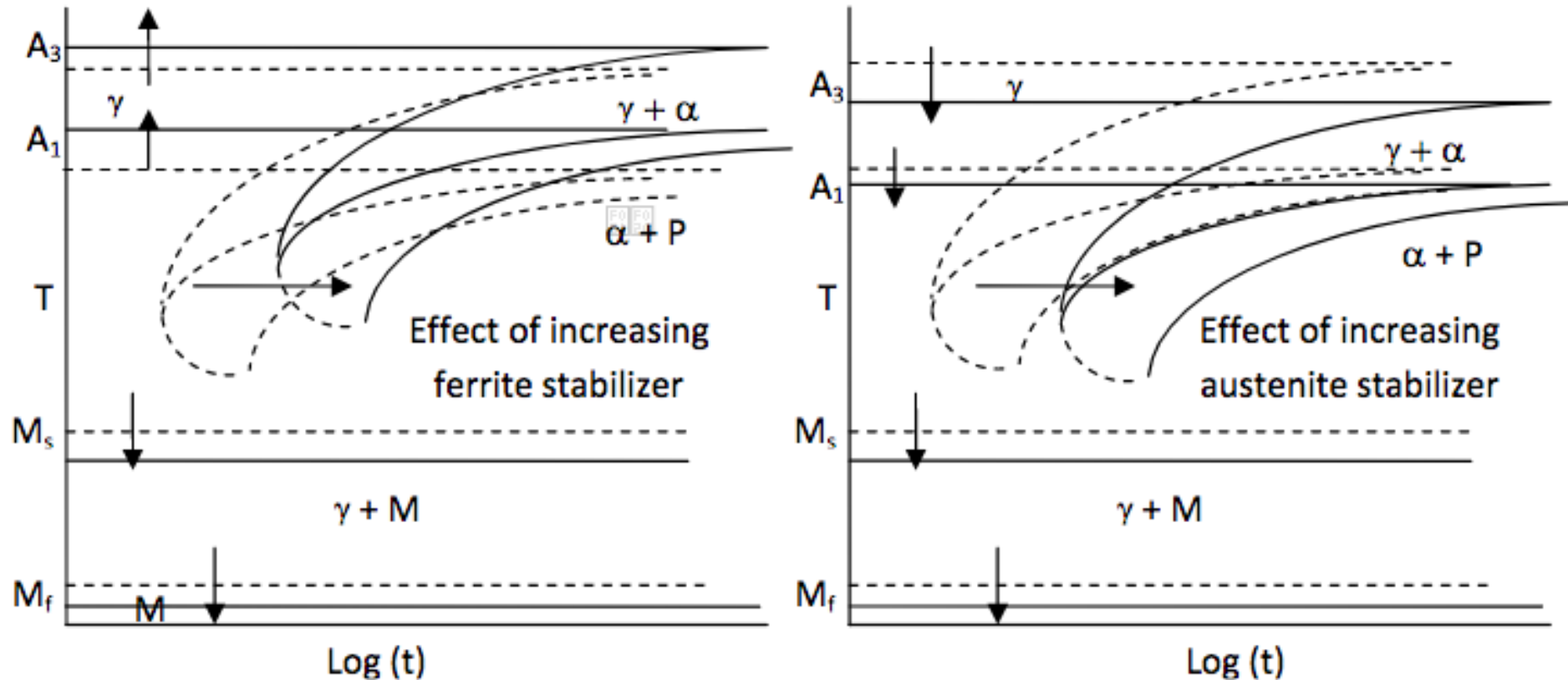
- ➢ Schematic representation of the effect of alloying elements on steel hardenability
- ➢ Both ferrite and austenite stabilizers dissolved in steel increase the hardenability

Effect of austenite grain size

- Hardenability increases if the diffusion controlled transformation reactions can be suppressed.

- The diffusion controlled transformations occur by nucleation and growth and grain boundaries are the preferred sites for nucleation.

- As the grain size of austenite ⬆, the total grain boundary area per unit volume ⬇, thereby the area available for nucleation of diffusion controlled transformation products ⬇

- An increase in austenite grain size thereby increases the hardenability of steel

Effect of austenite grain size
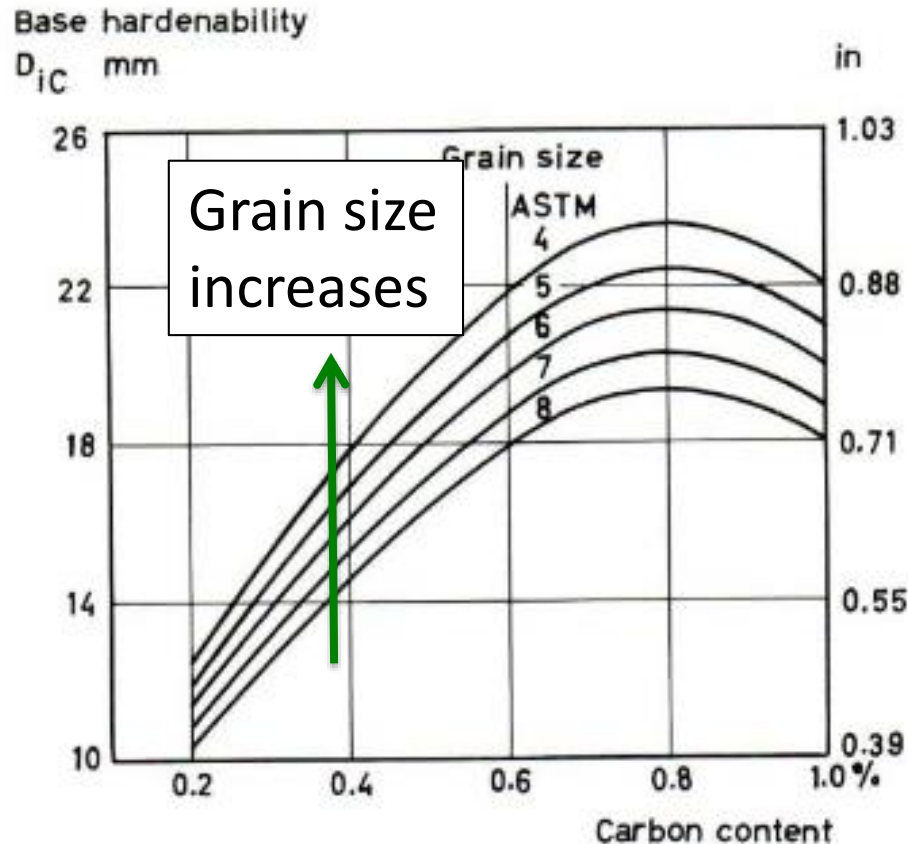
➢ Plot showing combined effect of grain size and C-content
➢ Although hardenability ⬆ as grain size ⬆, it is not preferred as large grain size reduces strength and toughness

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Characterization of hardenability

➢ Several ways exist to express the hardenability of steels. Some examples are:

– As the maximum rod diameter which can be fully hardened by martensitic transformation.

– Another way is by measuring the slowest cooling rate that allows for complete martensitic transformation in the whole cross section.

The depth of hardening will be adopted in this course as the measure of hardenability.

The employed method is called Jominy hardenability test or end-quench test

Jominy end quench test
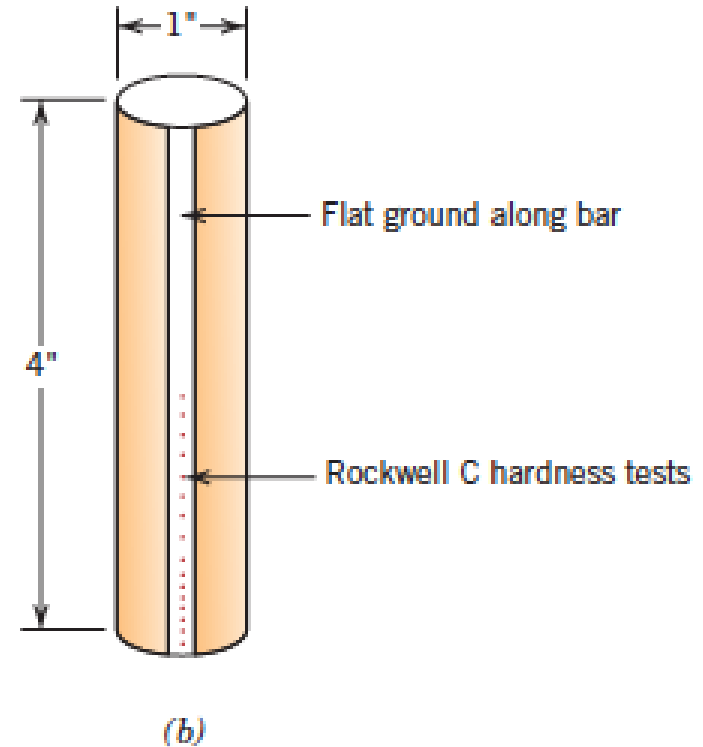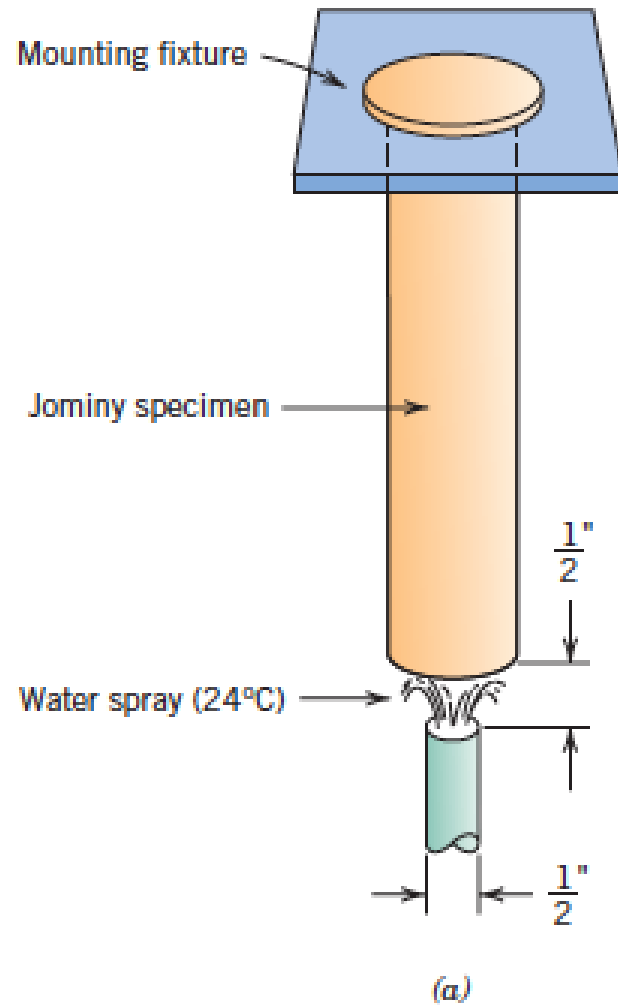
Jominy end quench test

➢ A cylindrical specimen with 25.4 mm diameter and 100 mm length is austenitized at a prescribed temperature for a specified time.

➢ After removal from furnace it is mounted as shown in the figure in slide 147

➢ The lower end of the cylinder is quenched by a jet of water of specified flow rate and temperature.

➢ After the specimen is cooled to room temperature, shallow flats of 0.4 mm depth are ground along specimen length and Rockwell C hardness is measured along this length starting from the quenched end

➢ A hardenability plot is obtained by plotting hardness as a function of distance from quenched end.

Hardenability plot from Jominy test
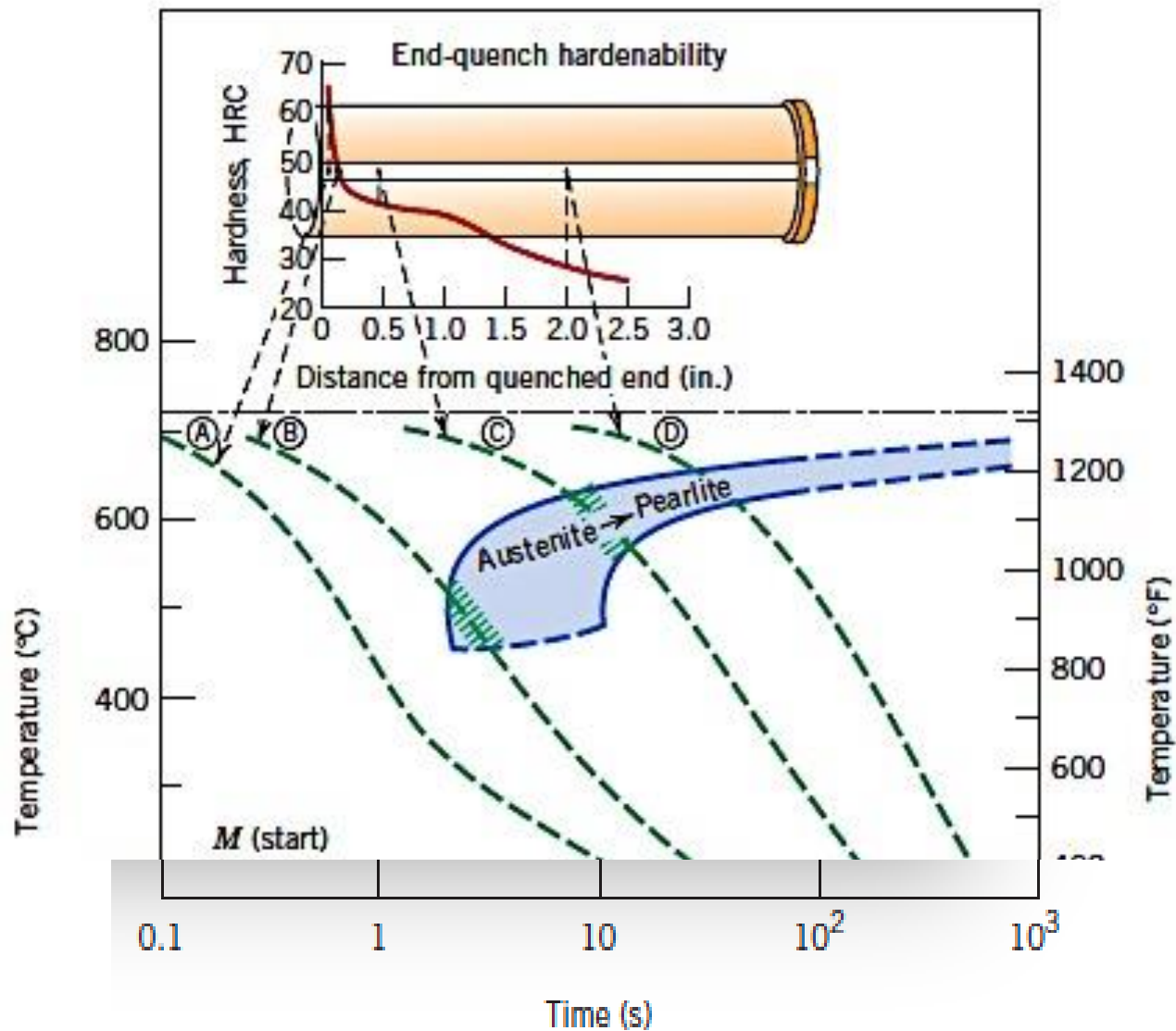
Hardenability plot from Jominy test

➤ The quenched end is cooled most rapidly and as 100% martensite is formed here, highest hardness is obtained at this point

➤ Cooling rate decreases with distance from the quench end and correspondingly hardness also decreases

➤ With decreasing cooling rate more time is allowed for carbon diffusion ➜ correspondingly pearlite or a mixture of pearlite, martensite and bainite may form

➤ A steel with high hardenability will retain high hardness at large distances ➜ the curve will be rather flat

➤ For a steel with low hardenability, hardness will start dropping soon ➜ the curve will be steeper

Steel composition & hardenability plot
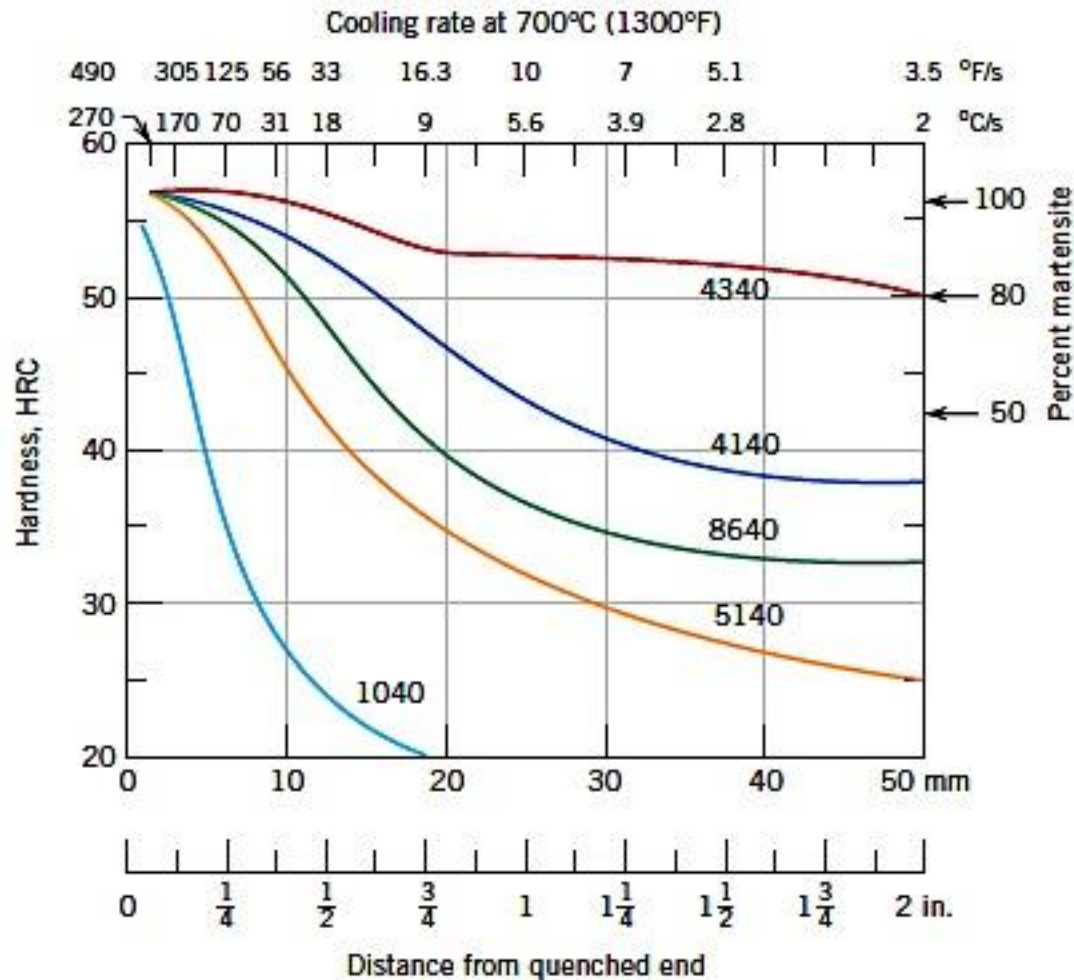
Hardenability plots of five different steels, each having 0.4 wt.% C