Phase transformations in steel

- The microstruture and mechanical properties of steel are controlled by the phase constituents
- The phase constitution on the other hand is controlled by the phase transformations occurring during processing and/or heat treatment
- For all practically important purposes of phase transformation in steels, the parent phase is austenite
- The transformation of steel can be either

  Isothermal: Transformation of austenite by holding at a fixed temperature below A_{c1}

  Continuous: Transformation of austenite when steel is being continuously cooled.

Austenite to ferrite transformation

- During equilibrium cooling (very slow cooling as in phase diagram) of hypoeutectoid steels austenite is transformed to proeutectoid ferrite between A_{c3} and A_{c1} temperatures
- The same transformation takes place isothermally, when hypoeutectoid steel is instantaneously cooled below A_{c1} (say to 600 °C) and held isothermally
- The $\gamma \rightarrow \alpha$ transformation is diffusive in nature and occurs by nucleation and growth.
- Nucleation occurs at grain boundaries and other structural defects.

Austenite to pearlite transformation

- Below the eutectoid temperature, austenite transforms to pearlite ➔ knowledge from phase diagram
- The transformation occurs by nucleation and growth
- The temperature of γ-transformation strongly influences the pearlite interlamellar spacing (λ_p) ➔ as transformation temperature ⬇, λ_p ⬇
- The lower the value of λ_p, the higher is the hardness of the steel ➔ as the transformation temperature ⬇, steel hardness ⬆

Pearlite formed at 700 degree C ➔ $\lambda_p = 10^{-3}$ mm, hardness 20 RC

Pearlite formed at 600 degree C ➔ $\lambda_p = 10^{-4}$ mm, hardness 30 RC

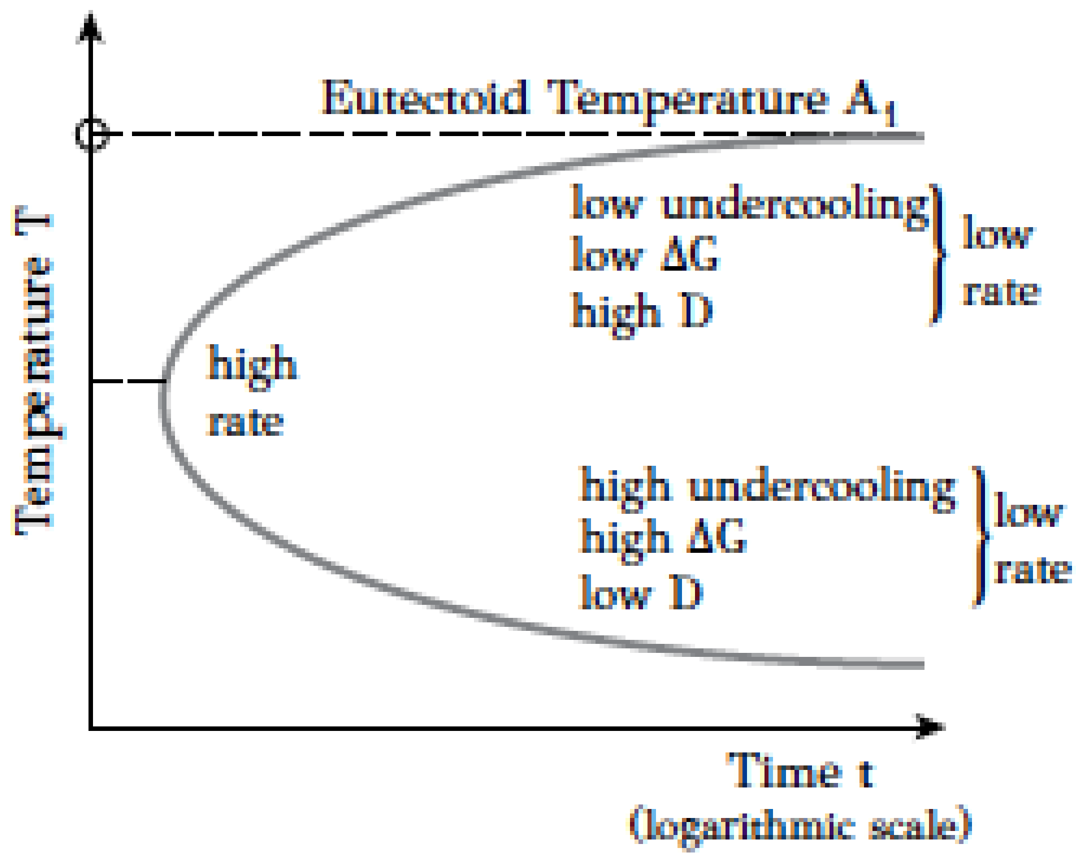
Austenite to pearlite transformation

Photomicrograph of coarse pearlite

Photomicrograph of fine pearlite

Austenite to pearlite transformation

The kinetics of austenite ➔ pearlite transformation follows a C-curve behavior



Austenite to pearlite transformation

- At high temperatures (just below A_{c1}, corresponding to low undercooling) the nucleation rate is small but the growth rate is high
- At low temperatures (corresponding to high undercooling) the nucleation rate is high but the growth rate is small
- In both these cases, the transformation rate is low
- The maximum transformation rate is accomplished at intermediate temperatures → C-shaped transformation curve

Austenite to martensite transformation

- Martensite (denoted as α') is a non-equilibrium structure which appears when the austenitized steel samples are rapidly cooled or quenched
- Being a non-equilibrium phase, martensite is not denoted on the Fe-Fe_3C metastable phase diagram

Martensite (Quenching) X 700

Typical needle shaped microstructure of martensite

Austenite to martensite transformation

- The transformation of austenite to martensite is diffusionless and shear-like in nature
- The cooling rate should be fast enough so that other competing transformations e.g. ferrite, pearlite or bainite do not occur
- During martensitic transformation, the FCC unit cell of austenite transforms to the BCT (body centered tetragonal) unit cell of martensite ➔ it is simply a body centered cube, elongated along a direction
- All the carbon atoms remain as interstitial impurity and constitute a supersaturated solid solution.

Austenite to martensite transformation

- The martensitic transformation is athermal in nature → it occurs instantaneously and at a very rapid speed
- The nucleation of martensite is heterogeneous and occurs at structural defects located at prior austenite grain boundaries
- For any steel the transformation starts and finishes at definite temperatures:

  M_s: martensite start temperature

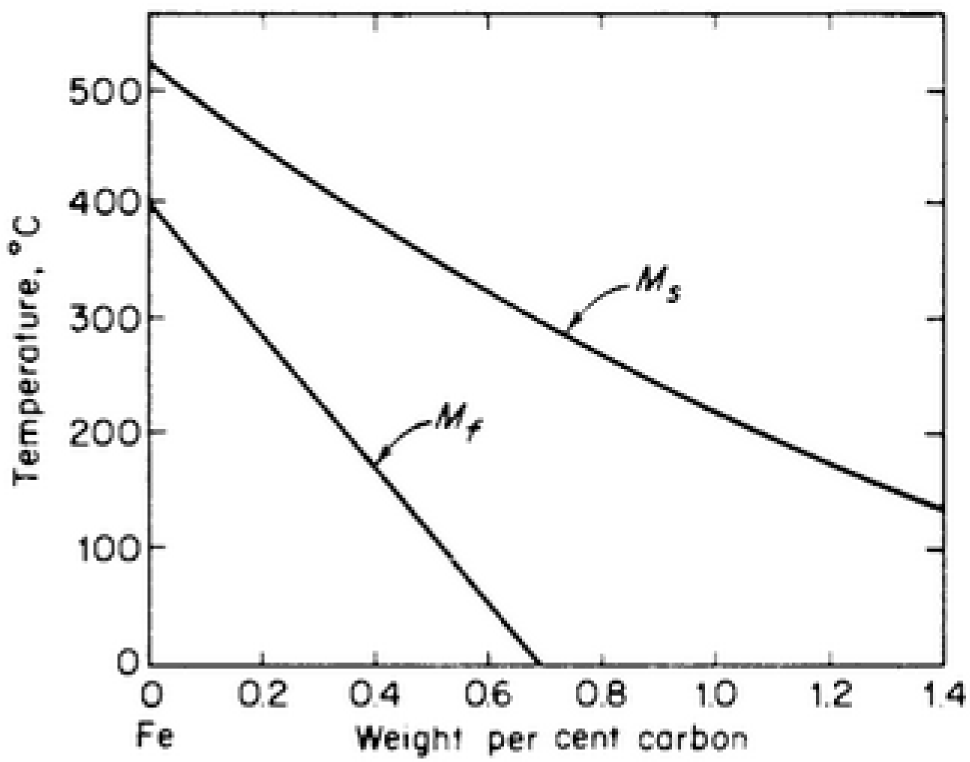
  M_f: martensite finish temperature

Austenite to martensite transformation

The M_s and M_f temperatures are strongly dependent upon the C-concentration and alloying element content

Effect of alloying element on M_s temperature

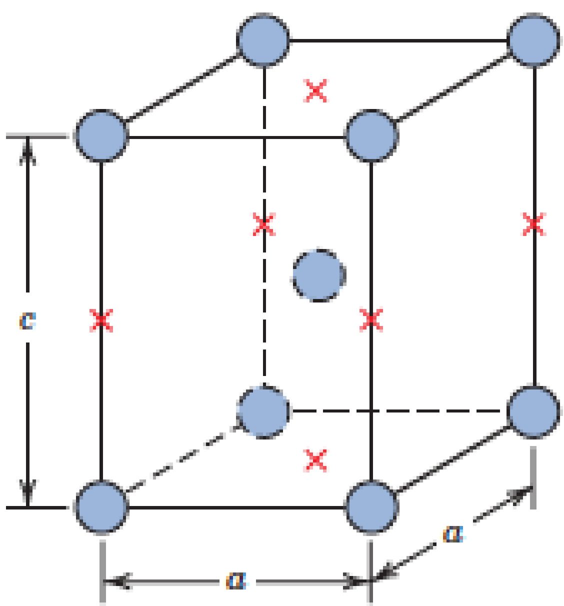
$$M_s(°C) = 539 - 463C - 30.4Mn - 17.7Ni - 12.1Cr - 7.5Mo$$



The M_f temperature typically ranges from 165 – 245 °C below the corresponding M_s temperature

Austenite to martensite transformation

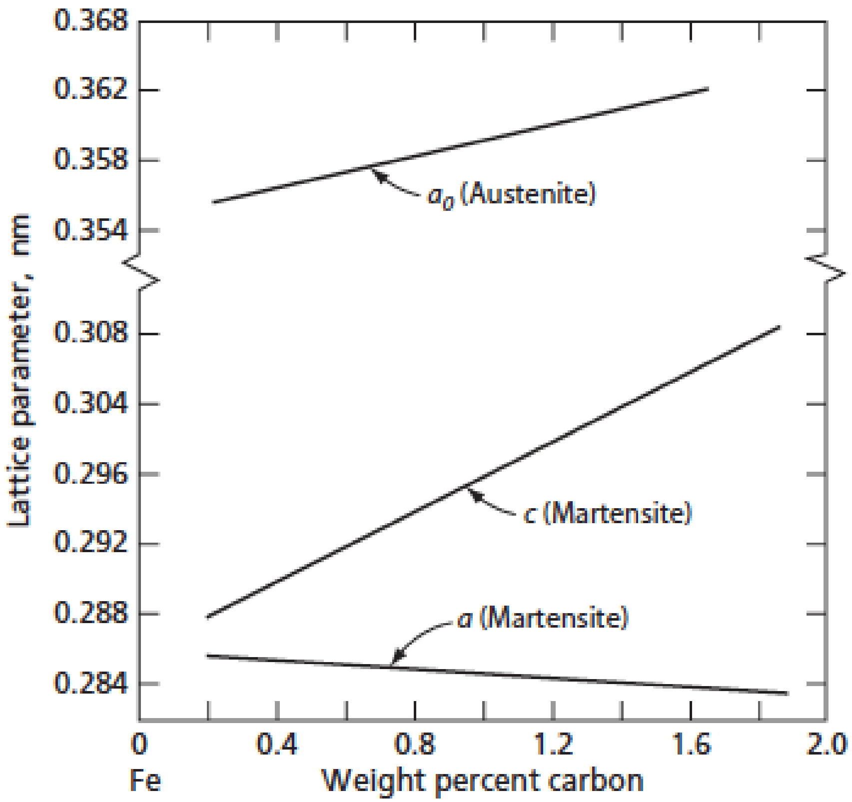
- The transformation of austenite to martensite is associated with an extremely high increase of hardness → of all phases of steel, martensite is the hardest
- The very high hardness of martensite is attributed to the presence of carbon at interstitial sites in the BCT lattice.



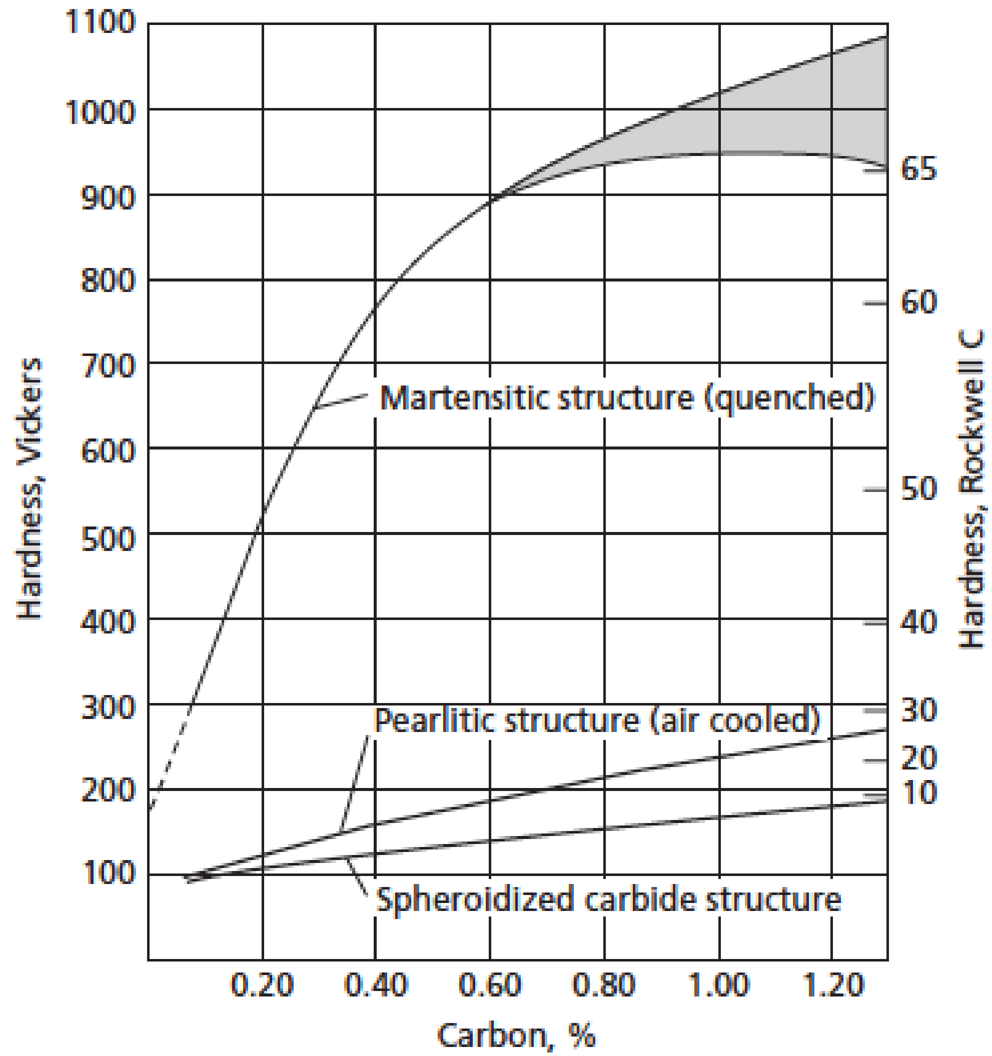
BCT unit cell of martensite

- Tetragonality of the unit cell (the c/a ratio) increases with C-content. The corresponding severe lattice distortions results into a highly strained unit cell and corresponding high hardness.

Austenite to martensite transformation



Evolution of martensite lattice parameters with C-content



Evolution of martensite hardness with C-content

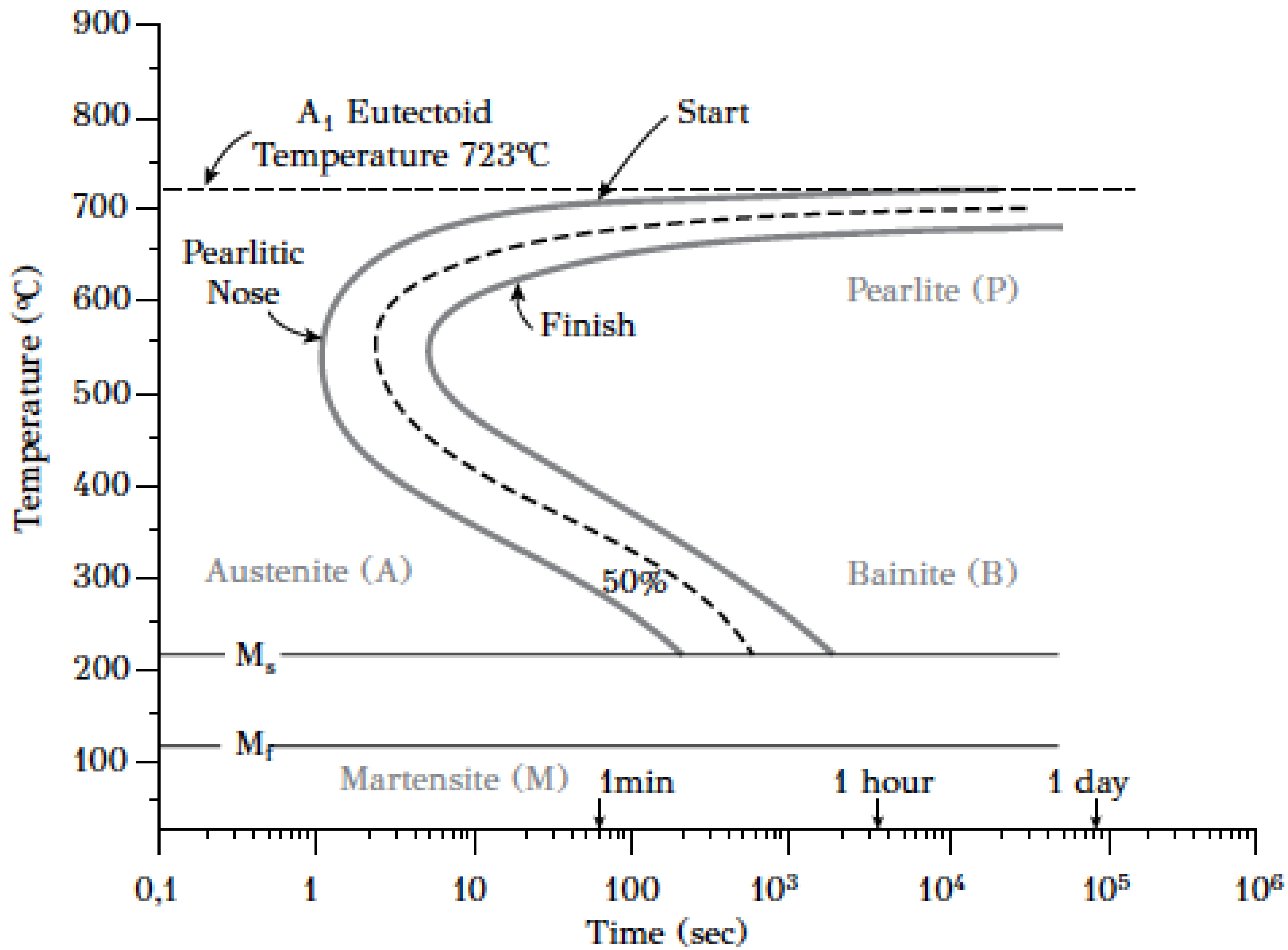
Austenite to bainite transformation

- Bainite forms by the decomposition of austenite at temperatures intermediate to pearlite formation and M_s-temperature.
- Bainite forms by the growth of ferrite followed by the precipitation of cementite as a result of carbon diffusion.
- Depending upon the transformation temperature, the bainite formed may be classified as upper bainite and lower bainite, respectively.

Isothermal transformation diagram

- Isothermal transformation diagram (or IT diagram) also known as time-temperature-transformation diagram (or TTT-diagram) is a useful tool to study non-equilibrium phase transformations in steel
- In isothermal transformation after austenitizing, the steel is cooled to a temperature below A_{c1} and then held isothermally to study the phase transformations.
- Several samples cut from the same bar are austenitized and then put in a salt baths maintained at different sub A_{c1} temperatures. After holding for certain times, the samples are quenched and their microstructure and hardness are measured.

Isothermal transformation diagram



IT diagram for a eutectoid steel

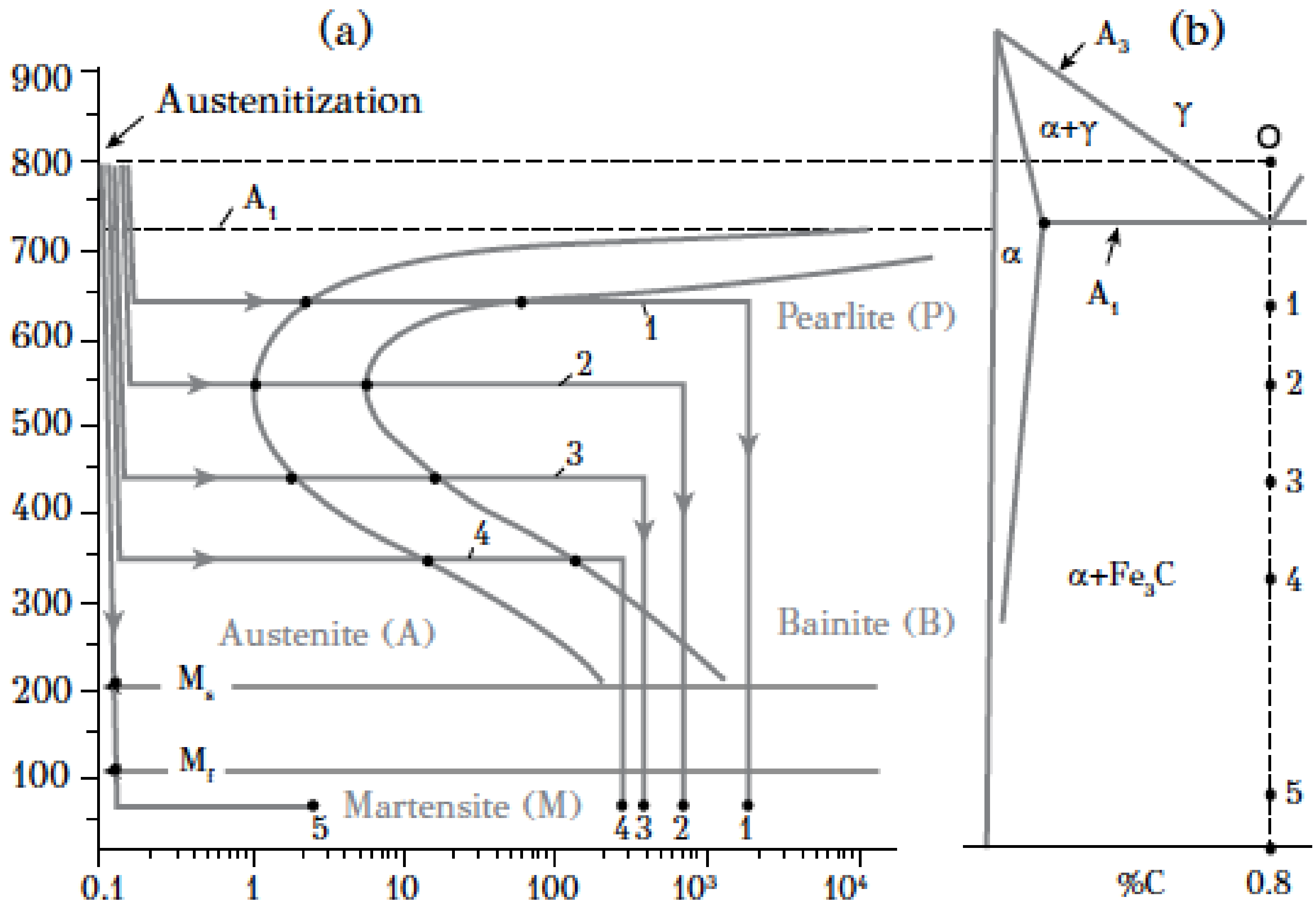
Isothermal transformation diagram

- This particular diagram is only valid for eutectoid composition. For other compositions the IT plot will have different shapes
- Vertical axis of the diagram is temperature and the horizontal axis is time, in logarithmic scale
- The two solid C-shaped curves correspond to the start and end of austenitic transformation to pearlite.
- The dotted C-curve intermediate between the two solid curves corresponds to 50% of transformation.
- In the upper portion of the curve, the pearlite start curve asymptotically approaches the A_{c1} line at large times

Isothermal transformation diagram

- The two horizontal lines at the lower portion of the curve denote M_s and M_f temperatures, respectively.
- The phase markings denote the respective regions where each phase forms during the isothermal transformation of austenite.
- The pearlitic nose denotes the temperature at which the maximum transformation rate is obtained. Upper bainite forms just below the nose region.

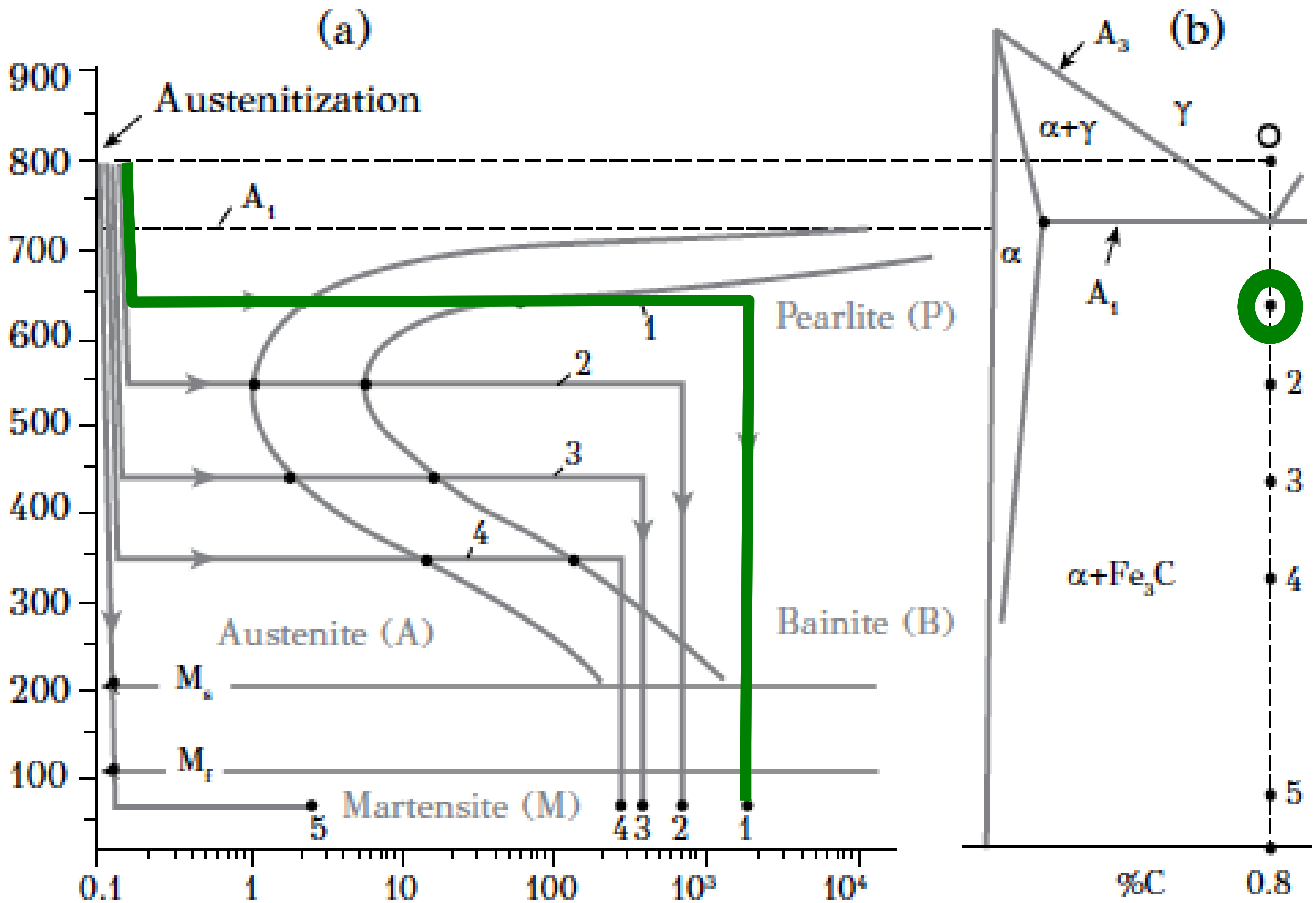
IT diagram – structure development



Schematic study of the structure development is carried out by the 5 isothermally held samples (line 1 - 5)

IT diagram – structure development

Line 1

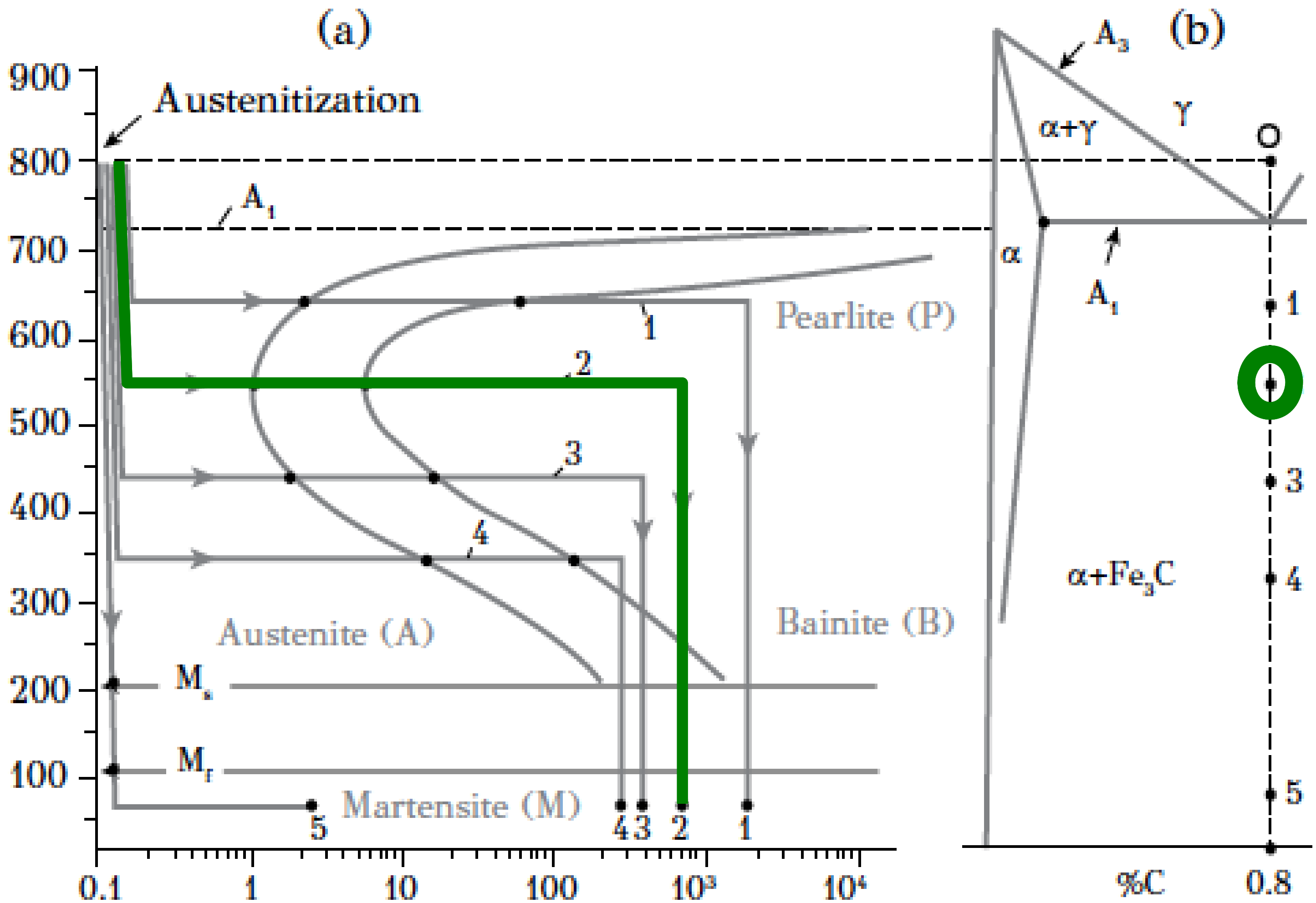


Isothermal transformation diagram

- Specimen 1 is rapidly cooled to 650 °C (a temperature rather close to A_{c1}), held there for 2000 sec. and then quenched to room temperature.
- The horizontal line crosses both the C-curve lines ➔ all the austenite has been transformed to pearlite
- The final microstructure will be 100% pearlite
- As the transformation temperature is high, the pearlite will be coarse with a low hardness.

IT diagram – structure development

Line 2

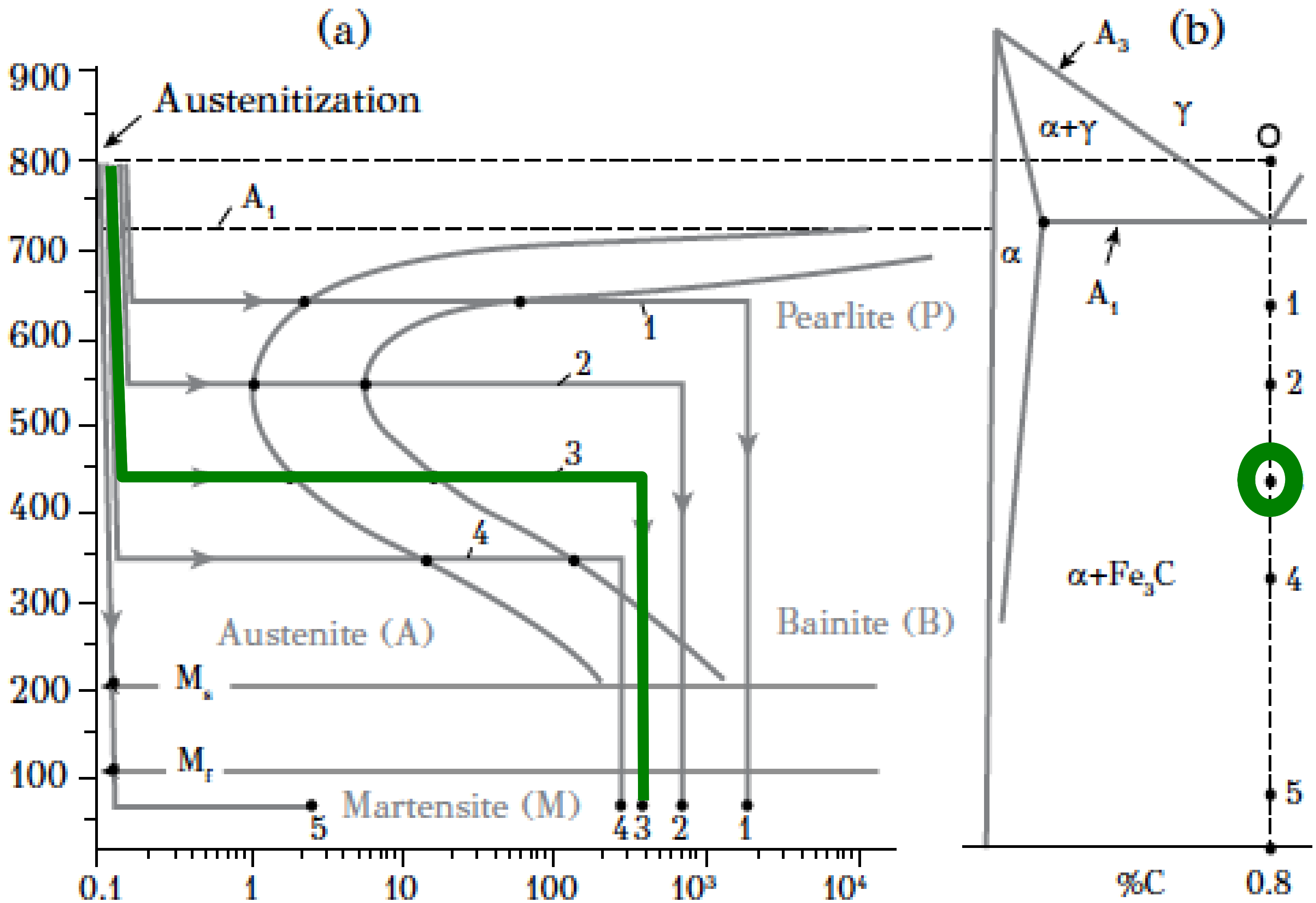


Isothermal transformation diagram

- Specimen 2 is rapidly cooled to 550 °C, held there for 700 seconds and then quenched to room temperature
- The two C-curves are cut at a temperature close to the pearlitic nose
- The final microstructure will be 100% pearlite
- Due to the lower transformation temperature, the pearlite will be fine, resulting in a high hardness

IT diagram – structure development

Line 3

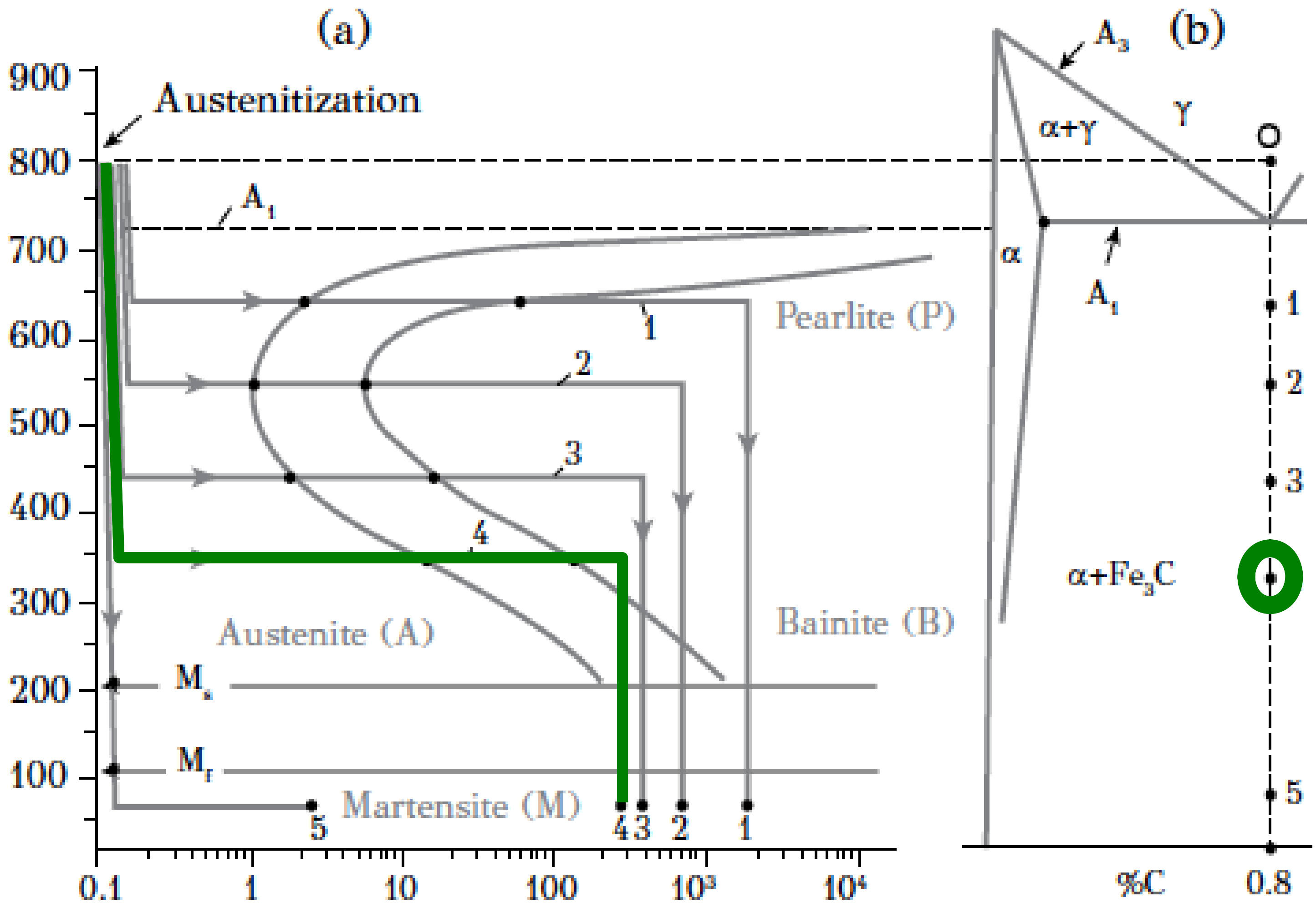


Isothermal transformation diagram

- Specimen 3 is rapidly cooled to 450 °C, held there for 300 seconds and then quenched to room temperature
- The two C-curves are cut at a temperature just below the pearlitic nose
- The final microstructure will be completely bainitic
- Due to the proximity of the transformation temperature to the pearlitic nose, the bainite is classified as upper bainite

IT diagram – structure development

Line 4

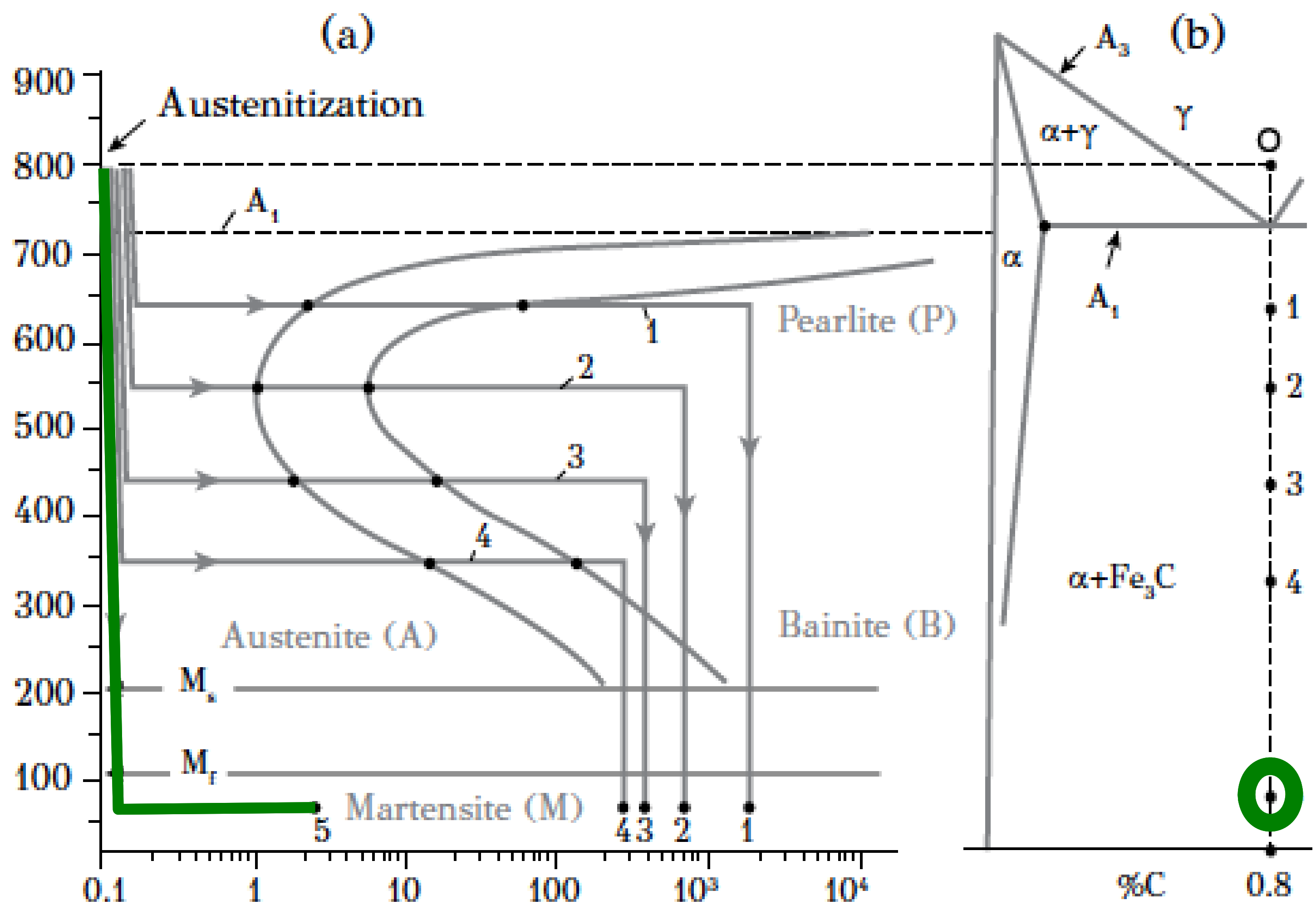


Isothermal transformation diagram

- Specimen 4 is rapidly cooled to 350 °C, held there for 200 seconds and then quenched to room temperature
- The two C-curves are cut at a temperature well below the pearlitic nose
- The final microstructure will be completely bainitic
- Due to the large distance of the transformation temperature to the pearlitic nose, the bainite is classified as lower bainite

IT diagram – structure development

Line 5



Isothermal transformation diagram

- Specimen 5 is rapidly cooled to room temperature
- The cooling curve does not cross any of the C-curves, but it crosses both the horizontal lines corresponding to M_s and M_f
- The final microstructure will be 100% martensite