Phase Transformations in Steels

Introduction to Phase Transformations

Phase transformations are fundamental to heat treatment processes. In steels, austenite (γ) transforms into various products depending on the cooling rate and alloy composition. The transformation sequence determines the final microstructure and properties of the material.

Thermodynamics and Kinetics of Transformations

Transformations occur when a phase becomes thermodynamically unstable. The driving force is the reduction in Gibbs free energy (ΔG). However, kinetics controls the rate and path of transformation. Two key mechanisms are:

• Diffusional Transformations (e.g., ferrite, pearlite, bainite)

• Diffusionless Transformation (e.g., martensite)

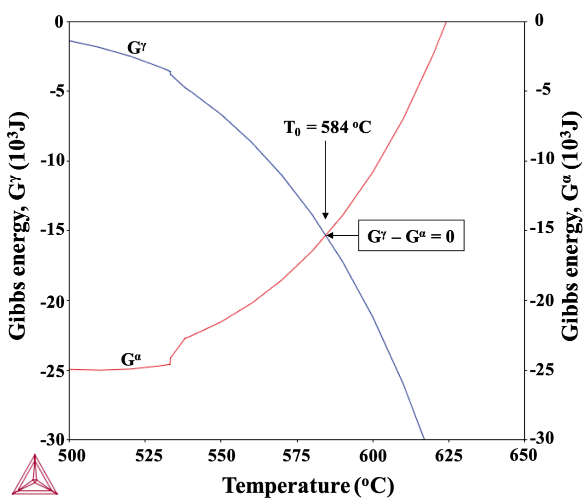


Figure 1. Gibbs free energy vs. temperature curves for γ (austenite) and α (ferrite) phases in steel, showing equilibrium at T_0 = 584 °C (Gγ = Gα). Adapted from Ibrahim & Adedayo (2022), FUDMA Journal of Sciences, 6(3), 15–21.

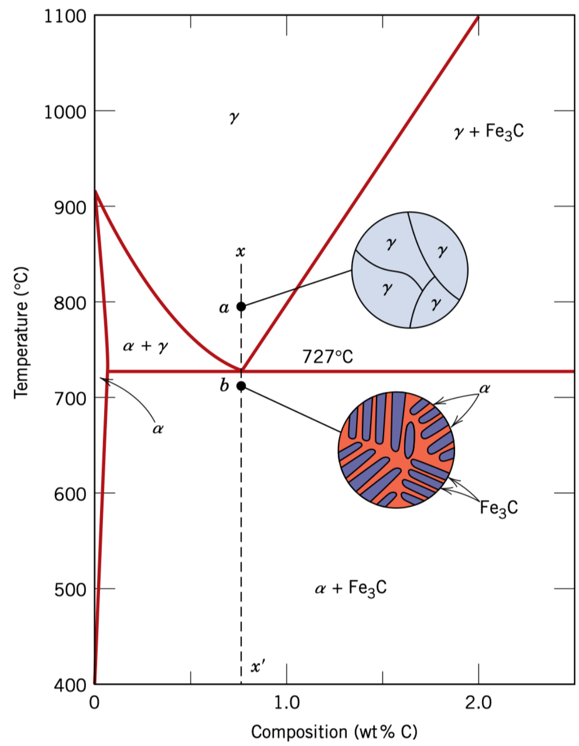
Ferrite and Pearlite Formation

• Ferrite (α): A BCC phase stable at lower temperatures and low carbon content. Forms first upon slow cooling.

• Pearlite: Eutectoid mixture of alternating ferrite and cementite lamellae. Forms at 727°C in eutectoid steel.

Transformation involves nucleation and growth. The lamellar spacing affects mechanical properties.

Figure 2. Schematic representations of the microstructures for an ironcarbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature. (Adapted from Callister & Rethwisch, 2014).



Hypoeutectoid vs. Hypereutectoid Steels

The Fe–Fe_3C phase diagram shows critical differences in microstructure development based on carbon content.

• Hypoeutectoid steels (0.02–0.76 wt% C):

Form proeutectoid ferrite before reaching the eutectoid temperature. At 727 °C, the remaining austenite transforms to pearlite.

→ Final microstructure: Ferrite + Pearlite.

• Hypereutectoid steels (0.76–2.14 wt% C):

Form proeutectoid cementite before reaching 727 °C. The remaining austenite transforms to pearlite.

→ Final microstructure: Cementite + Pearlite.

The distribution of proeutectoid and eutectoid phases influences:

- Hardness

- Machinability

- Wear resistance

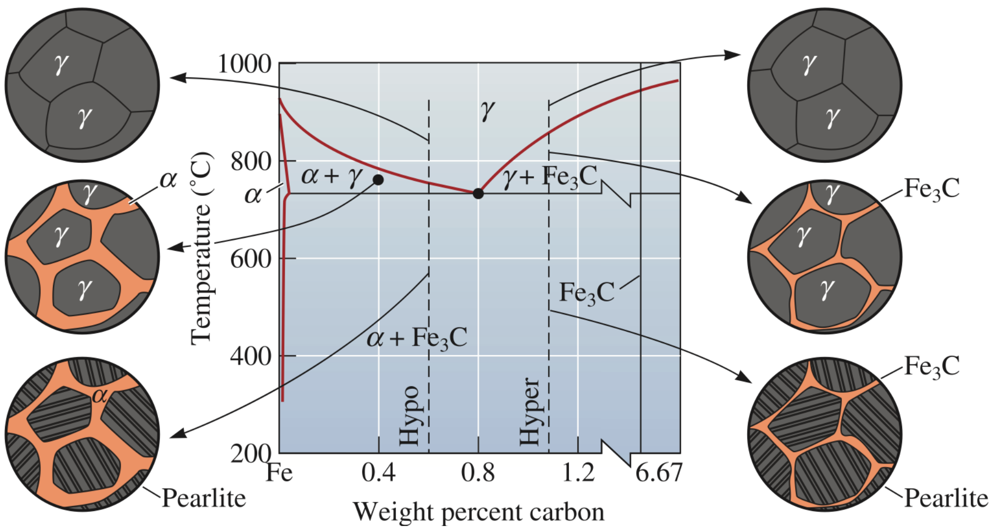


Figure 3. The evolution of the microstructure of hypoeutectoid and hypereutectoid steels during cooling, in relationship to the Fe-Fe_3C phase diagram. (Adapted from Askeland, 2016).

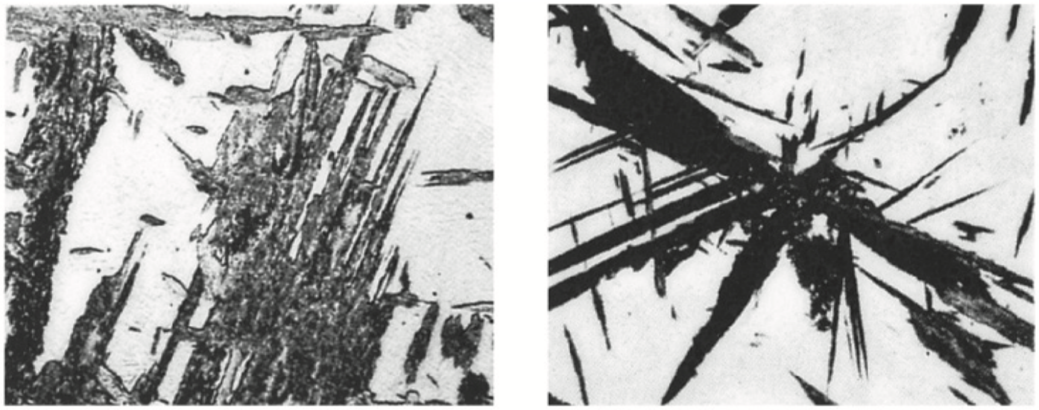
Bainite Formation

Bainite forms at temperatures lower than pearlite but higher than martensite. The microstructure depends on the transformation temperature:

• Upper bainite: formed at higher temperatures, feathery structure.

• Lower bainite: formed at lower temperatures, finer needles with carbides inside.

It combines strength with some ductility.

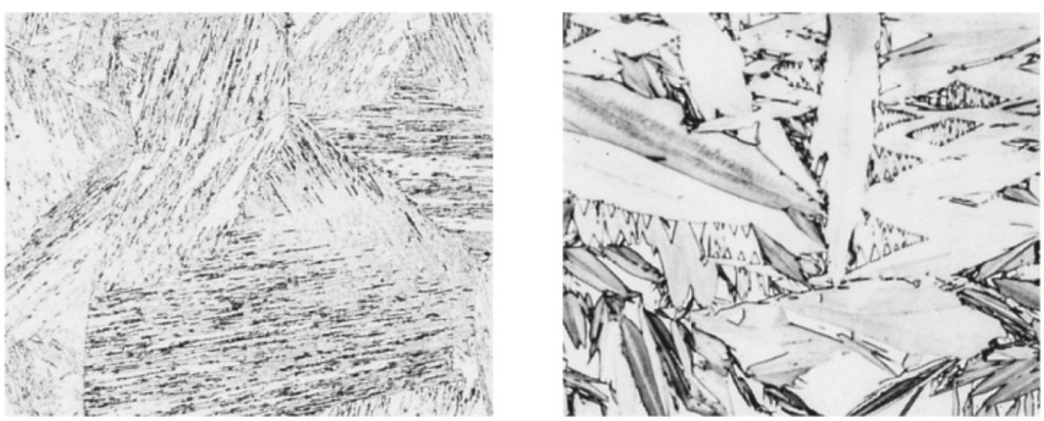


(a) (b)

Figure 4. (a) Upper bainite (gray, feathery plates) (× 600). (b) Lower bainite (dark needles) (× 400). (From ASM Handbook, Vol. 8, (1973), ASM International, Materials Park, OH 44073-0002.) Adapted from Askeland & Wright, 2020.

Martensitic Transformation

Martensite forms during rapid quenching when atoms do not have time to diffuse. It is a supersaturated solid solution of carbon in a BCT lattice. Martensitic transformation is shear-driven, with no diffusion involved. It produces very high hardness but brittleness.



(a) (b)

Figure 5. (a) Lath martensite in low-carbon steel (* 80). (b) Plate martensite in highcarbon steel (* 400). (From ASM Handbook, Vol. 8, (1973), ASM International, Materials Park, OH 44073-0002.). Adapted from Askeland & Wright, 2020.

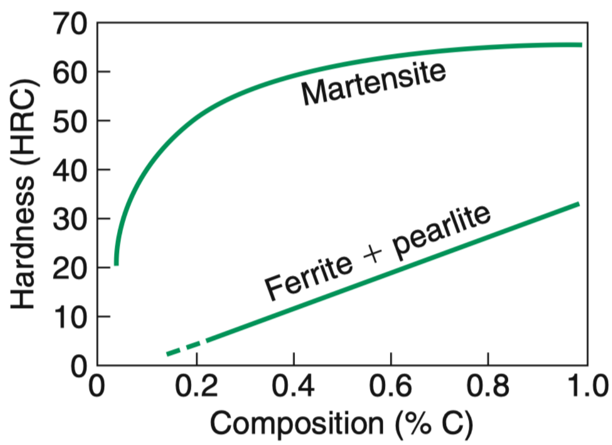


Figure 6. Variation of Brinell hardness with carbon content for fine pearlite and martensite in steels. Martensite exhibits significantly higher hardness compared to fine pearlite, especially in hypoeutectoid compositions.

Cooling Rate and Microstructure Control

The phase transformation product depends on the rate of cooling. Time-Temperature-Transformation (TTT) and Continuous Cooling Transformation (CCT) diagrams help visualize these effects.

• Slow cooling → Ferrite + Pearlit

• Intermediate cooling → Bainit

• Rapid quenching → Martensite

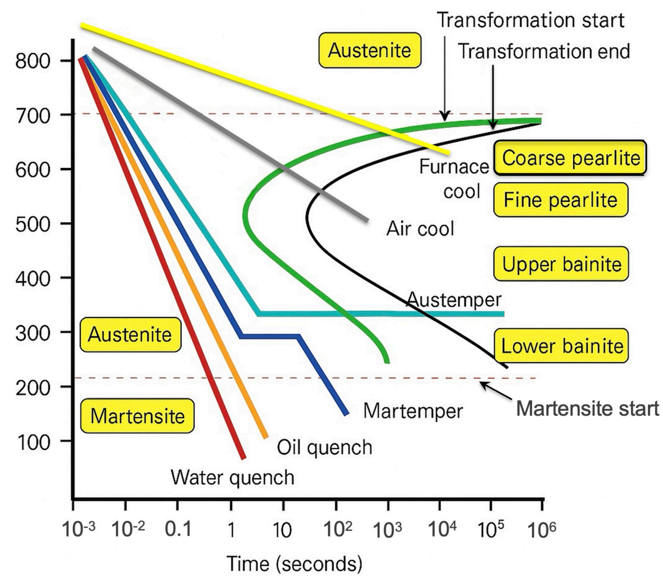


Figure 6. Time-Temperature-Transformation (TTT) diagram showing cooling curves for various quenching methods, including furnace cooling, air cooling, oil quenching, water quenching, austempering, and martempering.

Industrial Relevance and Applications

• Pearlite: Used in rails, wires, and springs for toughness and strength.

• Bainite: Employed in gears and automotive components requiring wear resistance.

• Martensite: Used in cutting tools and hardened shafts.

Controlling the cooling rate allows tailoring the microstructure for the desired application.

Summary

• Austenite decomposition products depend on temperature, time, and alloying.

• Each transformation route results in a distinct microstructure and properties.

• Understanding transformation pathways is critical in designing heat treatments.

Industrial Case Study: Unexpected phase formation during rapid cooling

Case: Components cooled rapidly showed martensite instead of expected ferrite–pearlite.

Cause: Engineers assumed equilibrium (phase diagram) instead of kinetics.

Lesson: Phase diagrams show *possibility*, not *actual transformation path*.