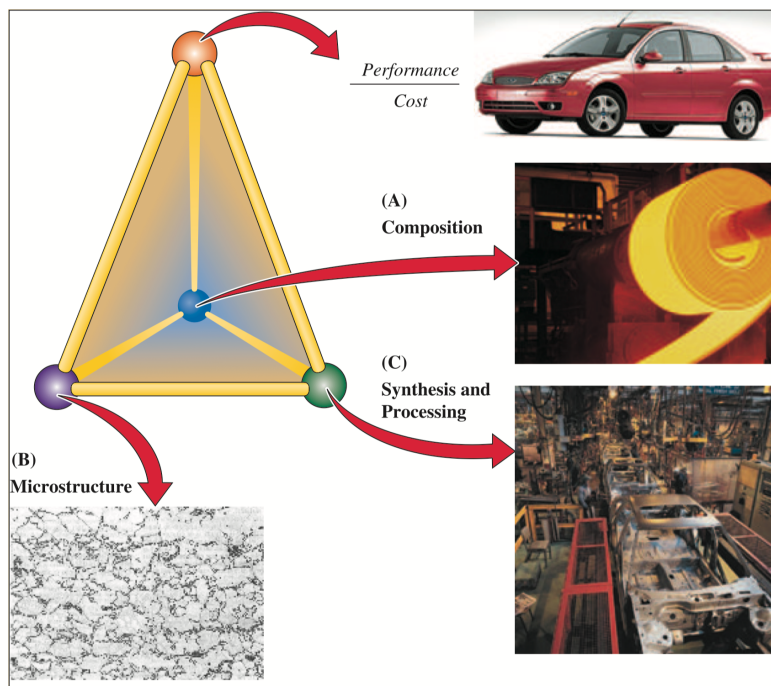


# Introduction to Heat Treatment

## Why Heat Treatment is Important in Materials Engineering

In engineering practice, material performance is not determined by chemical composition alone. Instead, it depends on the interaction between composition, processing, and microstructure.

Heat treatment is a key processing method that allows engineers to control microstructure—and therefore mechanical properties—without changing the chemical composition or shape of a component. By adjusting temperature and time, heat treatment enables optimization of strength, hardness, toughness, and service performance for specific applications.



## Industrial Case Study: Brittle fracture of untreated steel shafts

**Case:** Carbon steel shafts used in machinery failed prematurely due to low toughness.

**Cause:** Steel was used in as-rolled condition with coarse pearlite.

## Heat-treatment lesson:

Composition alone does not control performance — **microstructure does.**

### Part A: Introduction to Ferrous Alloys and the Iron–Iron Carbide Phase Diagram

Ferrous alloys are metallic materials primarily composed of iron. They are broadly classified into steels and cast irons based on carbon content. Steels typically contain up to 2.1% carbon, whereas cast irons contain more.

The Iron–Iron Carbide (Fe–Fe<sub>3</sub>C) phase diagram is a key tool in understanding phase transformations in steels. It shows the stability of different phases like ferrite ( $\alpha$ ), austenite ( $\gamma$ ), cementite (Fe<sub>3</sub>C), and pearlite as a function of temperature and carbon content.

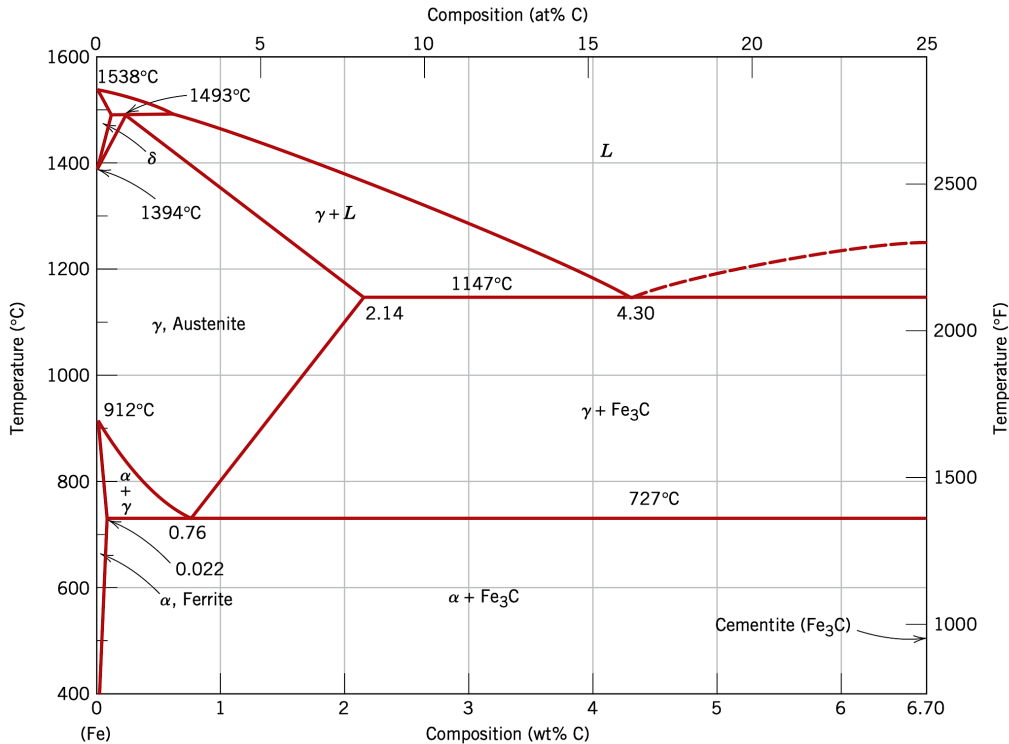
The eutectoid point, occurring at 0.76% C and  $\sim 727^\circ\text{C}$ , is especially important for heat treatment. It represents the transformation of austenite into pearlite. This transformation underpins many heat treatment processes such as annealing, normalizing, and hardening.

### Phase Transformations in Steels

Upon heating and cooling, steels undergo several phase transformations:

- Ferrite ( $\alpha$ )  $\leftrightarrow$  Austenite ( $\gamma$ )
- Austenite ( $\gamma$ )  $\leftrightarrow$  Pearlite (lamellar mixture of  $\alpha$  + Fe<sub>3</sub>C)
- Austenite ( $\gamma$ )  $\leftrightarrow$  Bainite (fine, acicular mixture of  $\alpha$  + Fe<sub>3</sub>C)
- Austenite ( $\gamma$ )  $\leftrightarrow$  Martensite (diffusionless, supersaturated solid solution)

The cooling path and rate (seen in TTT and CCT diagrams) determine which transformation products form.



**Figure 1.** Iron–Iron Carbide (Fe–Fe<sub>3</sub>C) phase diagram. (Adapted from Callister & Rethwisch, 2014).

## Steel Classification and Designation

Steels are categorized by carbon content:

- Low carbon steel (C < 0.25%) – good ductility and weldability
- Medium carbon steel (0.25%–0.6%) – balanced strength and ductility
- High carbon steel (C > 0.6%) – high hardness and strength

The AISI-SAE system designates steels by a 4-digit code. Example: 1040 = plain carbon steel with ~0.40% C.

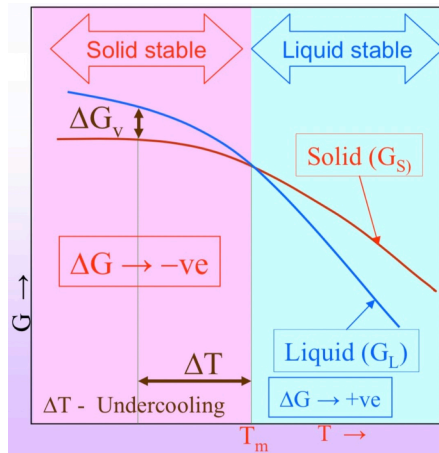
## Part B: Phase Formation and Thermodynamics

Heat treatment relies on phase transformations governed by thermodynamics and kinetics. At any given temperature and composition, each phase in steel has a specific Gibbs free energy (G). The phase with the lowest free energy is thermodynamically preferred and therefore stable.

A phase transformation becomes thermodynamically possible when a change in temperature causes the free energy of a new phase to become lower than that of the existing phase, resulting in a reduction in Gibbs free energy ( $\Delta G < 0$ ). This reduction provides the driving force for transformation. The larger the free energy difference between phases, the stronger the driving force.

Throughout this course, phase transformations will be interpreted as thermodynamically driven ( $\Delta G < 0$ ) but kinetically controlled by diffusion and time. Although free energy determines which phase is favored, the phase that actually forms depends on whether atoms have sufficient time to rearrange by diffusion during cooling.

**Figure 2.** Variation of Gibbs free energy (G) with temperature for solid and liquid phases. The intersection at the melting temperature ( $T_m$ ) represents equilibrium. Below  $T_m$ , the solid phase has lower free energy and is thus thermodynamically stable; above  $T_m$ , the liquid is more stable. The driving force for solidification ( $\Delta G$ ) increases with undercooling ( $\Delta T$ ).



Gibbs free energy is a thermodynamic quantity that reflects the balance between atomic bonding energy and atomic disorder in a material. As temperature changes, the relative free energies of different phases also change, altering their stability. At any given temperature, the phase with the lowest Gibbs free energy is thermodynamically stable. When cooling causes the free energy of one phase to become lower than that of another, a phase transformation becomes thermodynamically favorable.

**With this understanding of phase stability and transformations, heat treatment can now be formally defined as a controlled process of heating and cooling metals to change their physical and mechanical properties without altering their shape.**

### **Purpose of Heat Treatment**

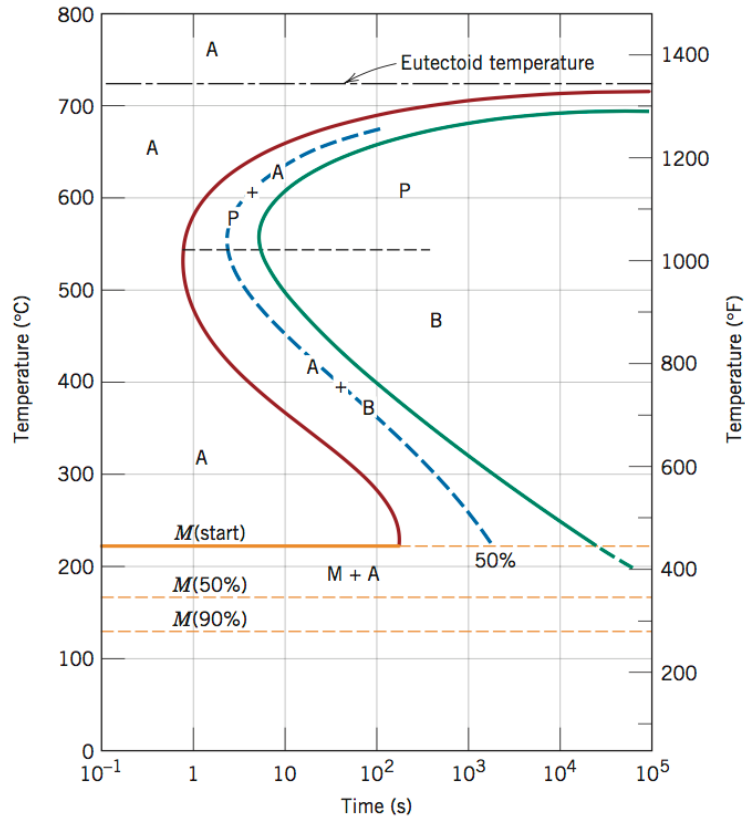
- Enhance hardness and strength.
- Increase ductility or toughness.
- Refine microstructure (e.g., grain size).
- Improve wear and corrosion resistance.
- Relieve internal stresses from manufacturing.

### **Classification of General Heat Treatment Processes**

- Annealing
- Normalizing
- Hardening (quenching)
- Tempering
- Surface Hardening
- Austempering and Martempering
- Age (Precipitation) Hardening

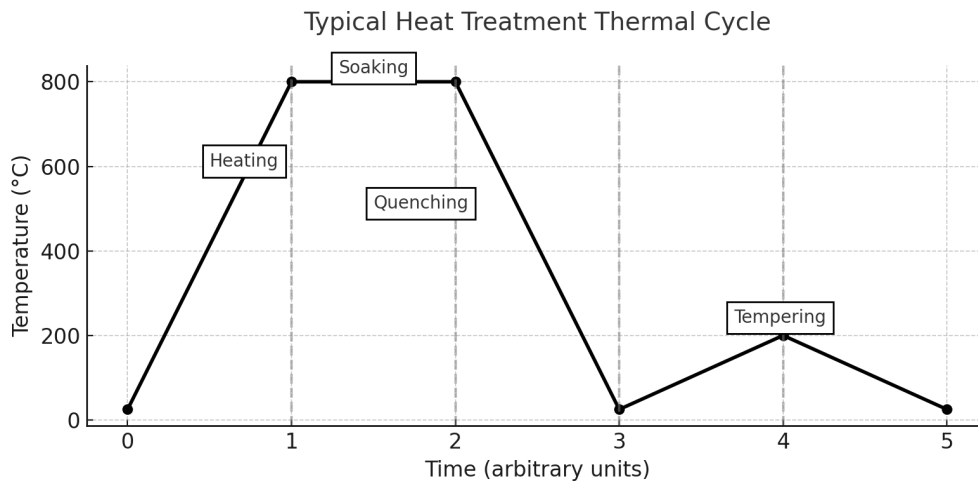
### **TTT and CCT Diagrams Overview**

TTT and CCT diagrams translate thermodynamic driving forces into practical heat treatment outcomes. They allow engineers to predict whether austenite will transform into pearlite, bainite, or martensite under specific cooling conditions.



**Figure 3.** The complete isothermal transformation diagram (TTT) for an iron–carbon alloy of eutectoid composition: A, austenite; B, bainite; M, martensite; P, pearlite. (Adapted from Callister & Rethwisch, 2014).

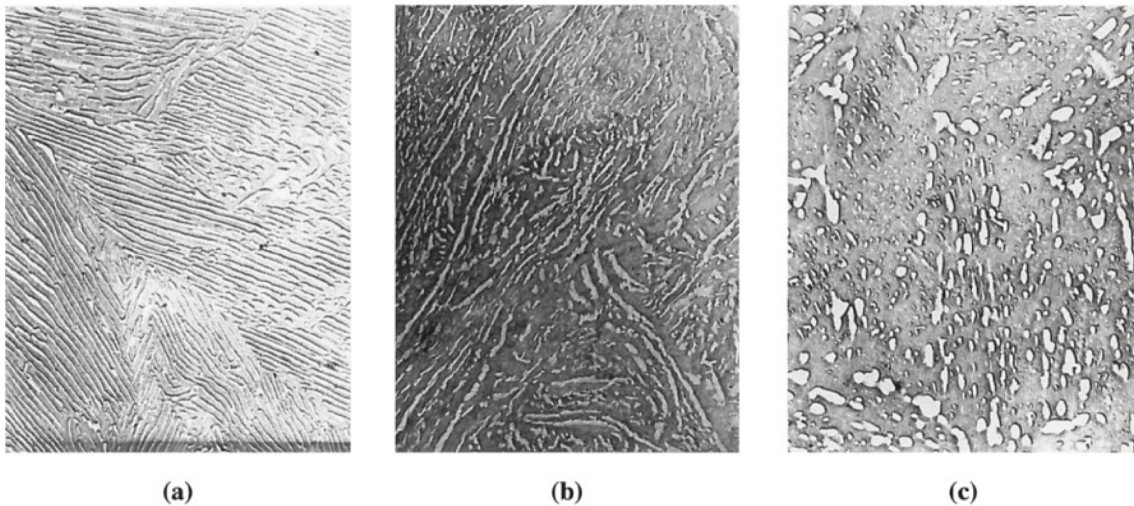
### Typical Thermal Cycle of Heat Treatment



**Figure 4.** A schematic diagram representing a heat treatment thermal cycle.

## Microstructure Before and After Heat Treatment

- Before: Ferrite + Pearlite (soft, ductile)
- After Quenching: Martensite (hard, brittle)
- After Tempering: Tempered Martensite (toughened, refined)



**Figure 5.** Micrographs of (a) pearlite, (b) bainite, and (c) tempered martensite, illustrating the differences in cementite size and shape among the three microconstituents ( $\times 7500$ ). (Adapted from Askeland & Wright, 2016).

## Mechanisms of Key Heat Treatment Processes

- Annealing – Recovery, Recrystallization, Grain Growth.
- Hardening – Austenite transforms to Martensite via rapid quenching; diffusionless transformation.
- Tempering – Decomposition of Martensite; formation of carbides; improved toughness.

## Engineering Applications of Heat Treatment

- Hardened and tempered steel tools (e.g., chisels, drills).
- Carburized gears and cams in automotive systems.
- Annealed copper for electrical wiring.
- Precipitation hardened aluminum in aerospace structures.