Heat Treatments of Steels – Annealing, Normalizing, and Spherodizing

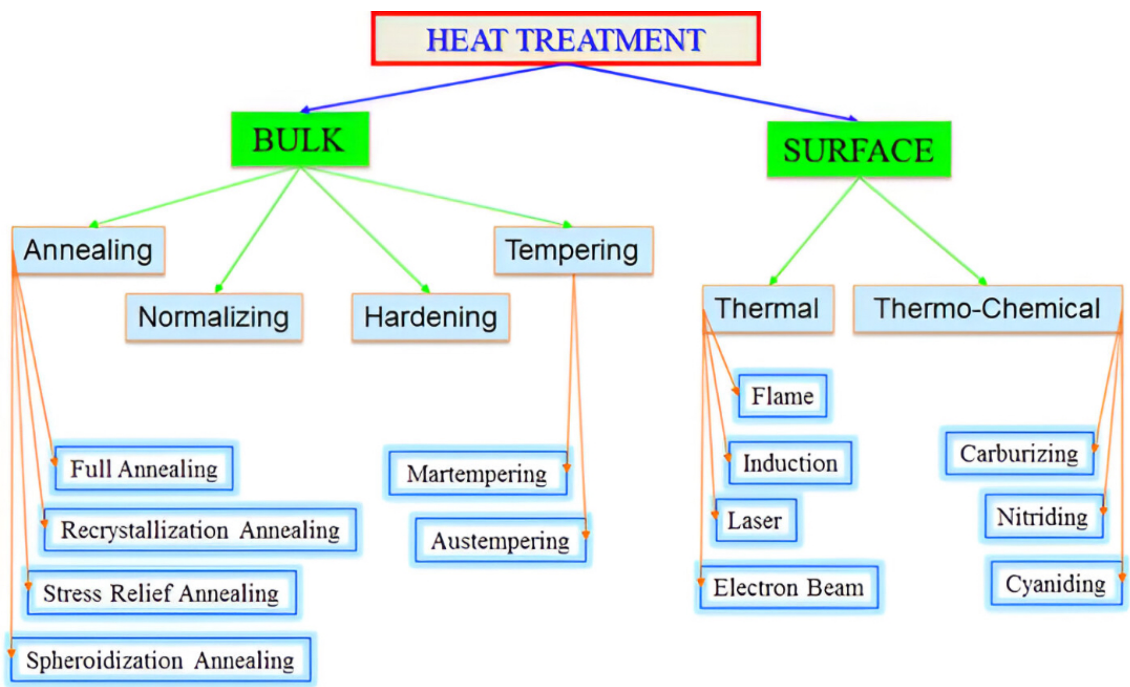
What is Heat Treatment?

Heat treatment is a thermal process used to modify the physical and mechanical properties of metals. It involves controlled heating and cooling to achieve desired microstructural and property changes. The main objectives are to improve ductility, increase strength, relieve internal stresses, and refine the grain structure.

Conventional Heat Treatments of Steels

Heat treatment techniques are generally classified into:

- Annealing
- Normalizing
- Hardening (e.g., quenching)
- Tempering
- Surface Hardening (e.g., carburizing, nitriding)



Annealing Processes Overview

Annealing is primarily used to reduce hardness, improve ductility, and prepare metals for further processing. The process involves heating to a specific temperature, holding (soaking), and slow cooling.

Types of Annealing:

- Full Annealing
- Process Annealing
- Stress Relief Annealing

Full Annealing

This process involves heating the steel above its upper critical temperature (Ac_3) to form austenite, followed by slow furnace cooling to produce a coarse pearlite or ferrite-pearlite structure. The aim is to achieve maximum softness and ductility.

Process Annealing

Used primarily for low-carbon steels, this involves heating below the lower critical temperature (Ac_1), typically between 550–650°C. It is used to restore ductility in cold-worked materials without inducing phase transformation.

Stress Relief Annealing

Residual stresses from machining, welding, or forming operations can be detrimental to dimensional stability and performance. Stress relief annealing involves heating the metal below Ac_1, holding it to allow stress relaxation, and slowly cooling.

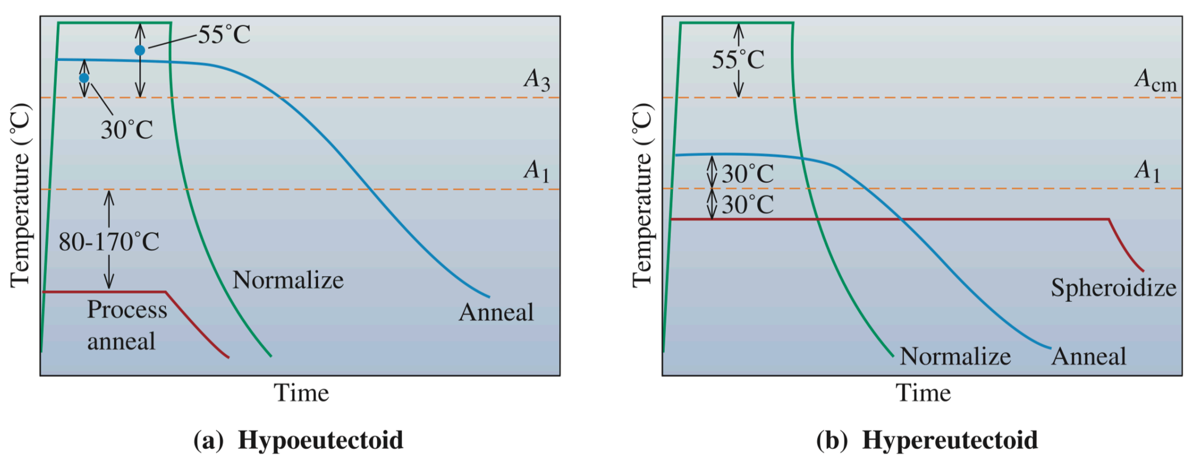


Figure 1. Schematic summary of the simple heat treatments for (a) hypoeutectoid steels and (b) hypereutectoid steels.

The Three Stages of Annealing

Annealing typically involves three metallurgical stages:

• Recovery – Substructure changes such as dislocation rearrangement. Reduction in residual stresses.
• Recrystallization – Formation of new, strain-free grains, leading to significant drop in strength and increase in ductility.
• Grain Growth – Continued heating causes larger grains to grow at the expense of smaller ones.

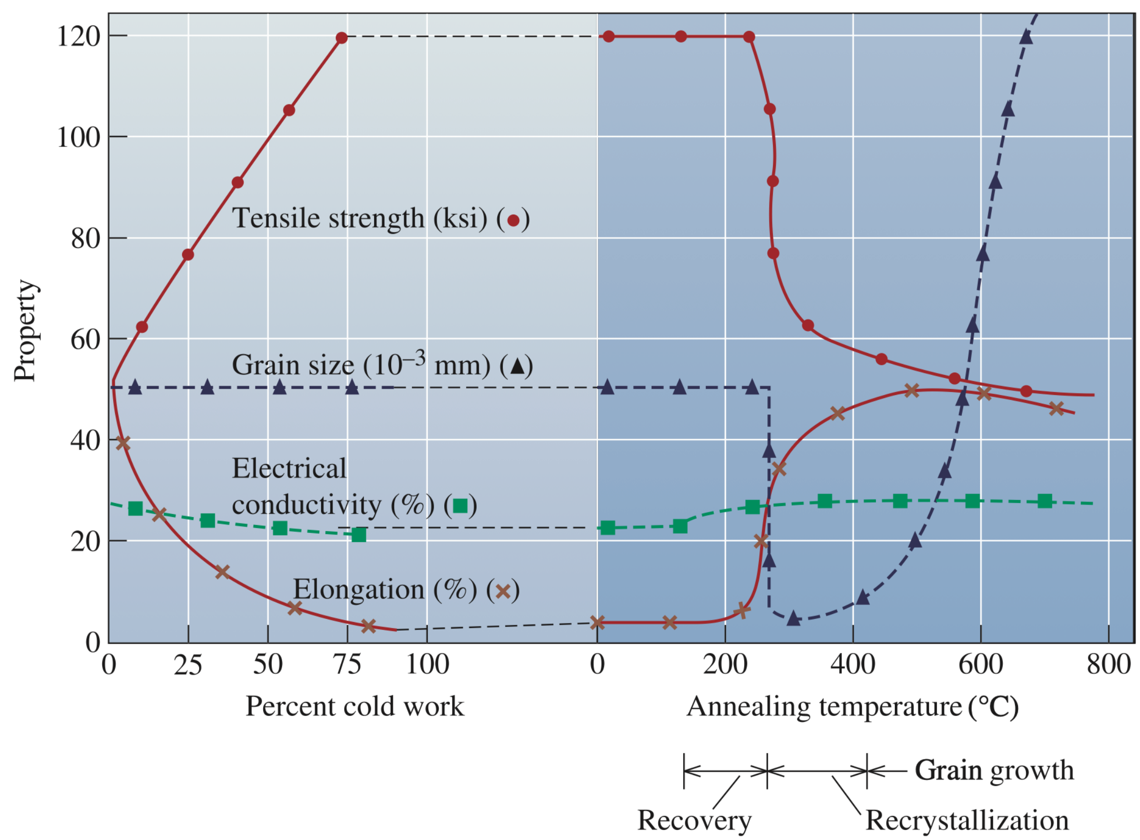
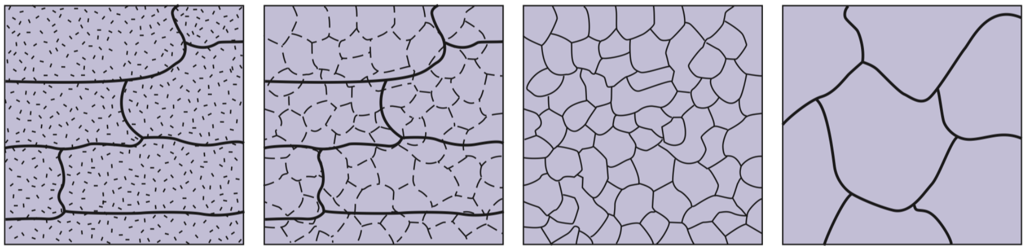


Figure 2. The effect of cold work on the properties of a Cu-35% Zn alloy and the effect of annealing temperature on the properties of a Cu-35% Zn alloy that is cold worked 75%. (Adapted from Askeland & Wright, 2016).



(a) (b) (c) (d)

Figure 3. The effect of annealing temperature on the microstructure of cold-worked metals. (a) Cold worked, (b) after recovery, (c) after recrystallization, and (d) after grain growth. (Adapted from Askeland & Wright, 2016).

Industrial Applications of Annealing

Annealing is widely used in metal forming industries to improve the formability of steel sheets. It's also used after welding to relieve residual stresses and before machining to stabilize dimensions.

Applications:

• Automotive body panels (process annealing)

• Pressure vessels (stress relief)

• Structural components (full annealing before shaping)

Summary

• Annealing enhances ductility and reduces hardness by promoting microstructural recovery and recrystallization.

• The type of annealing depends on the carbon content and intended application.

• Understanding thermal cycles and metallurgical changes is essential for heat treatment design.

Control of Annealing

- Cold working increases strength by increasing dislocation density, but reduces ductility.
- Annealing is applied after cold working to restore ductility and to control grain size.
- Proper annealing design requires knowledge of recrystallization temperature and recrystallized grain size.

Recrystallization Temperature (T^R)

- Recrystallization temperature is the temperature at which new, equiaxed, strain-free grains begin to form in a cold-worked material.
- The driving force for recrystallization is the stored internal energy introduced during cold working.
- Recrystallization temperature is **not a fixed material property**; it depends on processing conditions.

Factors Affecting Recrystallization Temperature

- Increasing the amount of cold work lowers the recrystallization temperature.
  - A minimum cold work of about **30–40%** is required for recrystallization.
- Smaller initial grain size lowers the recrystallization temperature by providing more nucleation sites.
- Pure metals recrystallize at lower temperatures than alloys.
- Increasing annealing time lowers the effective recrystallization temperature.
- Recrystallization temperature increases with melting temperature and is approximately:

  $T_R \cong 0.4, T_m$ (in K)

Recrystallization Temperature and Metal Working

- Deformation **below** the recrystallization temperature is called **cold working**.
- Deformation **above** the recrystallization temperature is called **hot working**.
- Approximate temperature ranges:
  - Cold working: < 0.3 T_m
  - Warm working: 0.3–0.6 T_m
  - Hot working: > 0.6 T_m
- These ranges are approximate and depend on material and processing conditions.

Recrystallized Grain Size

- Lower annealing temperature and shorter annealing time produce finer grains.
- Increasing the amount of cold work reduces final grain size by increasing nucleation sites.
- Second-phase particles can restrict grain growth depending on their size and distribution.

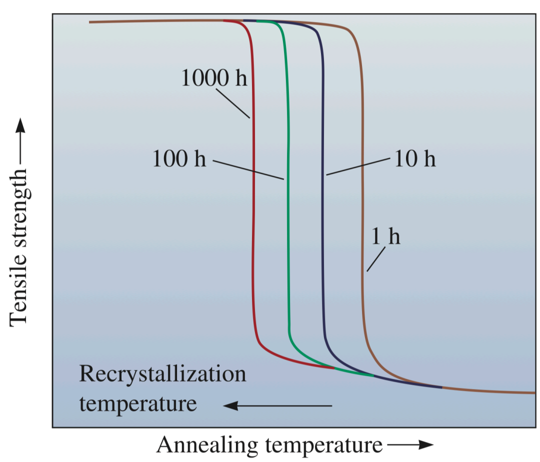


Figure 4. Longer annealing times reduce the recrystallization temperature. Note that the recrystallization temperature is not a fixed temperature. (Adapted from Askeland & Wright, 2016).

Industrial Case Study: Cracking during cold forming

Case: Sheet steel cracked during deep drawing.

Cause: Excessive cold work without intermediate annealing.

Lesson: Annealing is essential to restore ductility after cold work.

Normalizing and Spheroidizing

Normalizing

Normalizing involves heating the steel to about 30–50°C above the upper critical temperature (Ac_3), holding it to form uniform austenite, and then air cooling. This process results in a fine pearlitic microstructure and refines grain size compared to full annealing.

Purpose and Benefits of Normalizing

• Refines grain structure for better mechanical properties.

• Eliminates structural inhomogeneities and non-uniform cooling effects.

• Improves dimensional stability and prepares steel for machining or further treatment.

• Typically produces higher strength and hardness than full annealing.

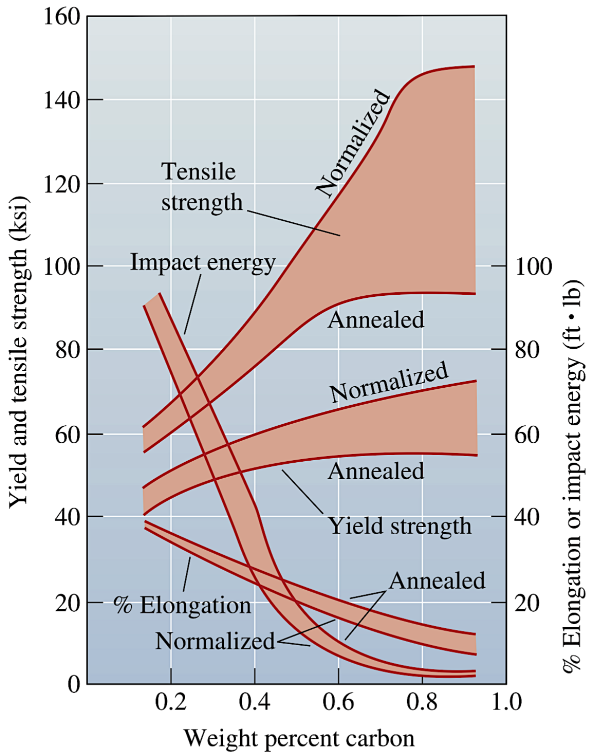


Figure 2. The effect of carbon and heat treatment on the properties of plain carbon steels. (Adapted from Askeland & Wright, 2016).

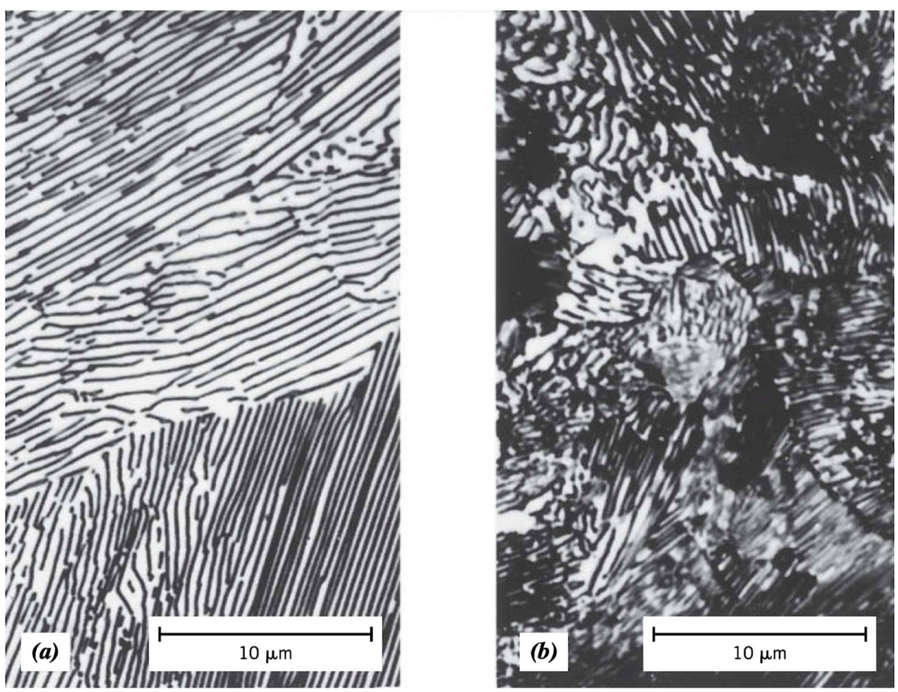


Figure 3. Photomicrographs of (a) coarse pearlite and (b) fine pearlite. 3000X. Adapted from Callister.

Spheroidizing

Spheroidizing is a heat treatment that transforms lamellar cementite in pearlite into rounded spheroids to reduce boundary area. This improves ductility and machinability in high-carbon steels.

The process is typically done:

• By prolonged heating just below the eutectoid temperature (around 700°C).

• By cycling above and below Ac_1 or by tempering quenched martensite.

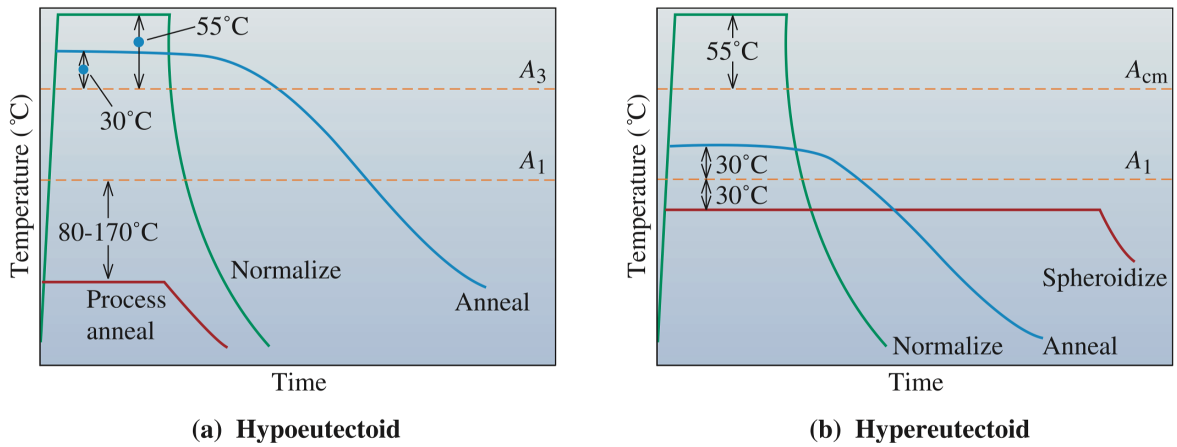


Figure 4. Schematic summary of the simple heat treatments for (a) hypoeutectoid steels and (b) hypereutectoid steels. (Adapted from Askeland & Wright, 2016).

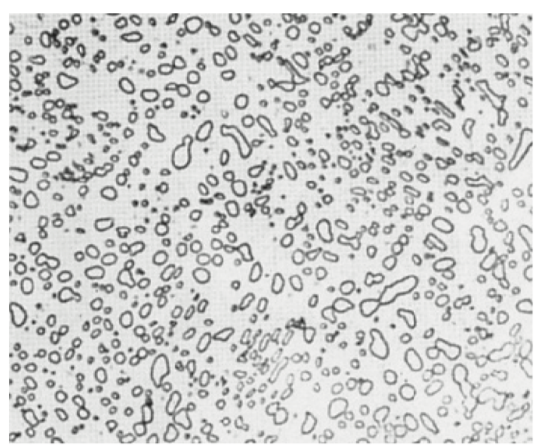


Figure 5. The microstructure of spheroidite with Fe3 C particles dispersed in a ferrite matrix (× 850). (Adapted from Askeland 2020).

Techniques of Spheroidizing

Several methods are used to induce spheroidization:

• Subcritical annealing – holding just below Ac_1 for an extended time.

• Cycling – repeated heating above and cooling below Ac_1.

• Tempering martensite at subcritical temperatures.

These methods are essential for tool steels and wire drawing applications.

Comparison of Annealing, Normalizing, and Spheroidizing

• Annealing: Slow furnace cooling results in coarse pearlite or ferrite-pearlite.

• Normalizing: Air cooling produces fine pearlite with better mechanical properties.

• Spheroidizing: Spherical carbides lower hardness and enhance machinability.

Summary

• Heat treatment processes can be controlled to achieve different microstructures and mechanical properties.

• Normalizing is effective for refining structure and enhancing strength.

• Spheroidizing is essential for high-carbon steels requiring high machinability.

Example:

Recommend temperatures for the process annealing, annealing, normalizing, and spheroidizing of 1020, 1077, and 10120 steels.

SOLUTION

From Figure 13-1, we find the critical A_1, A_3, or A_{cm}, temperatures for each steel. We can then specify the heat treatment based on these temperatures.

Steel Type	1020	1077	10120
Critical temperatures	A_1 = 727°C A_3 = 830°C	A_1 = 727°C	A_1 = 727°C A_{cm} = 895°C
Process annealing	727 − (80 to 170) = 557°C to 647°C	Not done	Not done
Annealing	830 + 30 = 860°C	727 + 30 = 757°C	727 + 30 = 757°C
Normalizing	830 + 55 = 885°C	727 + 55 = 782°C	895 + 55 = 950°C
Spheroidizing	Not done	727 − 30 = 697°C	727 − 30 = 697°C

Industrial Case Study: Non-uniform mechanical properties in forgings

Case: Large forged parts showed variable hardness and strength.

Cause: Uneven cooling after forging; no normalizing.

Lesson: Normalizing refines grain size and homogenizes microstructure.