Quench and Temper Heat Treatments

Quenching Process

Quenching is the rapid cooling of steel from the austenitizing temperature to transform austenite into martensite. The quenching medium and rate significantly affect the final microstructure and properties. Common quenching media include:

- Water – very fast cooling, high risk of cracking.
- Oil – slower cooling, lower risk of stress.
- Air – used for air-hardening steels.

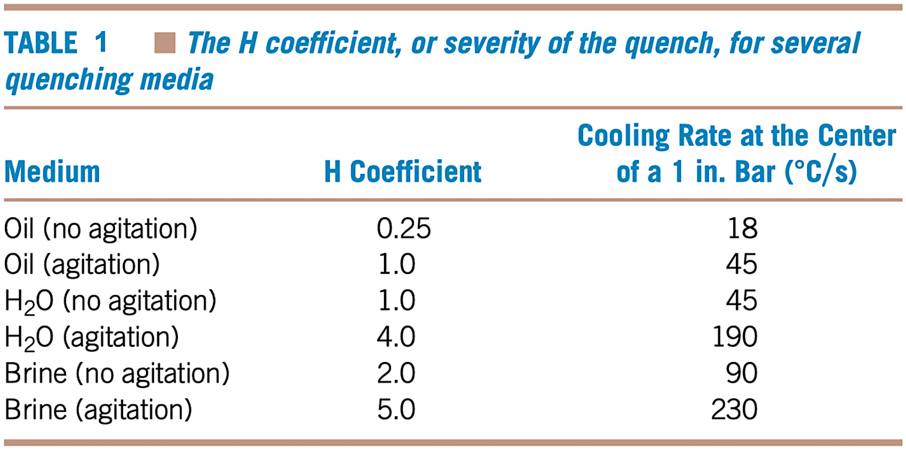


TABLE 1 ■ ***The H coefficient, or severity of the quench, for several quenching media***

Medium	H Coefficient	Cooling Rate at the Center of a 1 in. Bar (°C/s)
Oil (no agitation)	0.25	18
Oil (agitation)	1.0	45
H_2O (no agitation)	1.0	45
H_2O (agitation)	4.0	190
Brine (no agitation)	2.0	90
Brine (agitation)	5.0	230

Problems Associated with Quenching

- **Retained Austenite**: Occurs when cooling isn't sufficient to complete martensitic transformation.
- **Residual Stresses**: Thermal gradients during quenching lead to stress development.
- **Cracking and Distortion**: Caused by high internal stresses, especially in large or complex shapes.

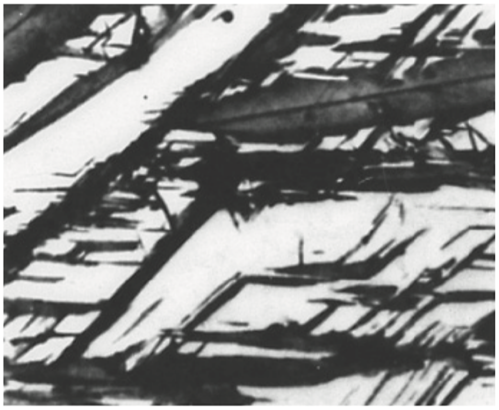


Figure 1. Retained austenite (white) trapped between martensite needles (black) (× 1000). (Adapted from Askeland & Wright, 2016).

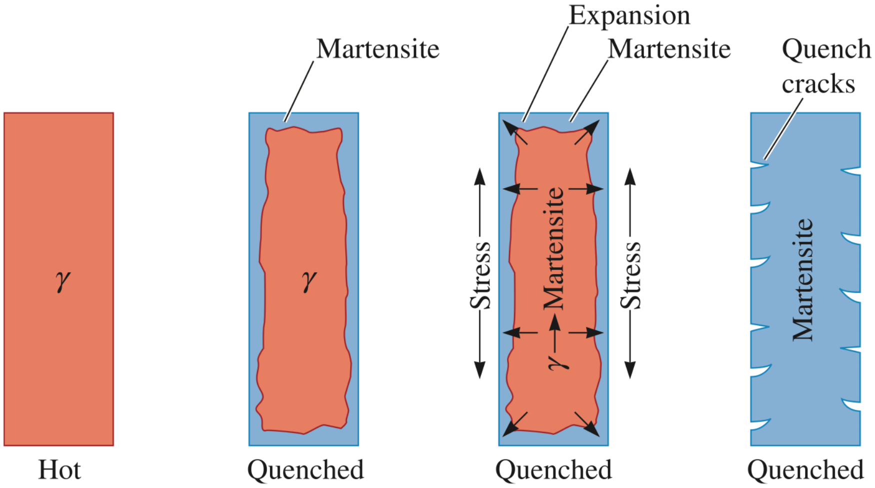


Figure 2. Formation of quench cracks caused by residual stresses produced during quenching. The figure illustrates the development of stresses as the austenite transforms to martensite during cooling. (Adapted from Askeland & Wright, 2016).

Tempering of Quenched Steels

Tempering involves reheating a quenched steel to a temperature below the eutectoid (Ac_1) point. It serves to:

- Relieve internal stresses.
- Increase toughness and ductility.
- Stabilize microstructure.

Stages of tempering include:

1. Formation of transition carbides.

2. Decomposition of retained austenite.
3. Coarsening of cementite and matrix softening.

Tempering Curves and Material Response

Tempering curves represent the change in hardness as a function of tempering temperature. They help select tempering conditions that yield the desired balance between strength and toughness.

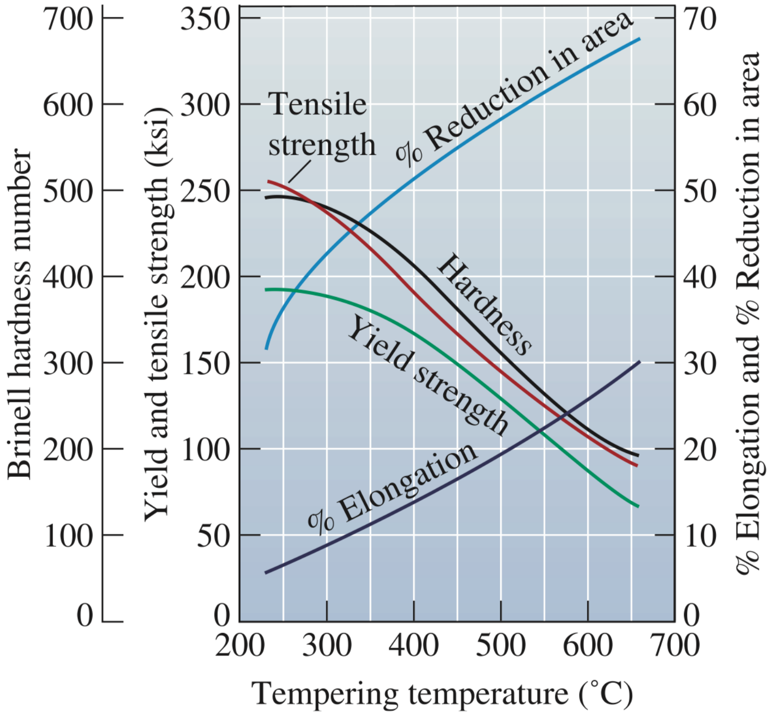


Figure 3. The effect oftemperingtemperature on the mechanical properties of a 1050 steel. (Adapted from Askeland & Wright, 2016).

Tempering Temperature Effects

Tempering temperature has a critical influence on the resulting microstructure and mechanical properties. Typical microstructural transformations during tempering include:

- Below 200°C: Formation of transition carbides (ε-carbide), minor drop in hardness.
- 200–400°C: Decomposition of martensite, formation of ferrite + fine cementite.

- 400–600°C: Coarsening of carbides, significant toughness recovery.
- Above 600°C: Risk of over-tempering, reduced strength and hardness.

Approximate hardness values after tempering (for 0.4–0.6 wt% C steels):

- As-quenched martensite: ~600 HV
- Tempered at 200°C: ~500 HV
- Tempered at 400°C: ~300 HV
- Tempered at 600°C: ~200 HV

Double Tempering and Microstructure Expectations

- Double tempering is often used for high-performance components like tool steels. The first temper transforms retained austenite, while the second temper stabilizes the structure, reducing internal stresses and enhancing toughness.
- Example: A tool steel tempered at 550°C twice for 1 hour each cycle shows better toughness and dimensional control than single tempering.
- Microstructure expectations by temperature:
  – 150°C: tempered martensite with some retained austenite
  – 350°C: ferrite matrix with fine carbides
  – 600°C: coarser ferrite + cementite, improved ductility

Practical Considerations

• Martempering is recommended for reducing thermal stresses during quenching.
• Double tempering is used for high-performance tools.
• Over-tempering must be avoided to prevent embrittlement or strength loss.

Example *Design of a Quench and Temper Treatment*

A rotating shaft that delivers power from an electric motor is made from a 1050 steel. Its yield strength should be at least 145,000 psi, yet it should also have at least 15% elongation in order to provide toughness. Design a heat treatment to produce this part.

SOLUTION

We are not able to obtain this combination of properties by annealing or normalizing (Figure 13-4); however, a quench and temper heat treatment produces a microstructure that can provide both strength and toughness. Figure 13-9 shows that the yield strength exceeds 145,000 psi if the steel is tempered below 460°C, whereas the elongation exceeds 15% if tempering is done above 425°C. The A_3 temperature for the steel is 770°C. A possible heat treatment is

1. Austenitize above the A_3 temperature of 770°C for 1 h. An appropriate temperature may be $770 + 55 = 825$°C.
2. Quench rapidly to room temperature. Since the M_f is about 250°C, martensite will form.
3. Temper by heating the steel to 440°C. Normally, 1 h will be sufficient if the steel is not too thick.
4. Cool to room temperature.

Summary

Quenching is essential for producing high-strength martensitic steels, but it introduces internal stresses. Tempering modifies the quenched microstructure, balancing strength with toughness. Careful control of both processes ensures optimal mechanical performance in engineering applications.

Quench Rate and Continuous Cooling Transformation (CCT) Diagrams

CCT Diagrams Overview

CCT diagrams show how steel transforms during continuous cooling, rather than under isothermal conditions. They are more representative of industrial heat treatment processes. CCT diagrams depend on steel composition and prior austenitization.

CCT vs. TTT Diagrams

TTT diagrams assume instantaneous quenching to a transformation temperature and isothermal holding. CCT diagrams track transformations during continuous cooling, as occurs during quenching.

- CCT diagrams are curved, while TTT diagrams have constant-time isotherms.
- Martensite start and finish lines are typically similar in both.

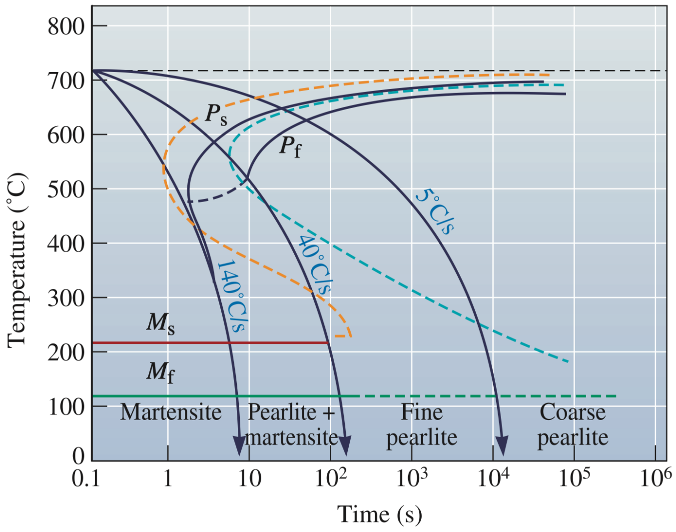


Figure 1. The CCT diagram (solid lines) for a 1080 steel compared with the TTT diagram

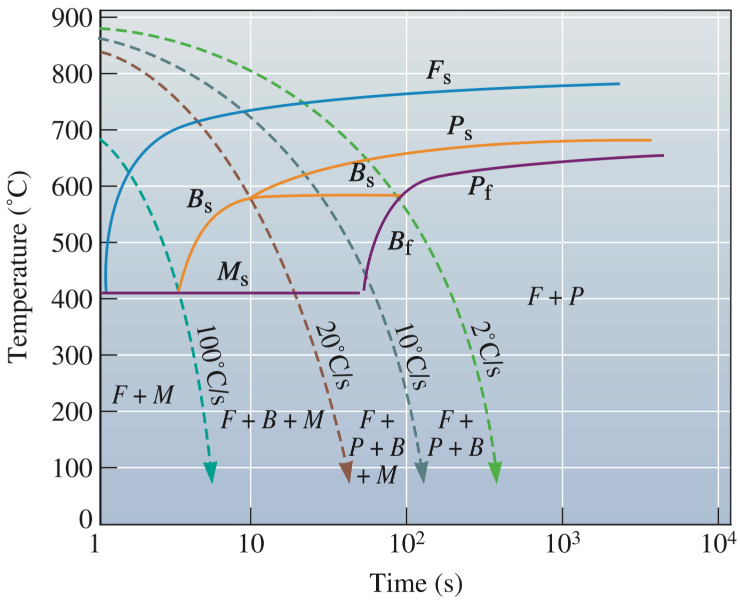


Figure 2. The CCT diagram for a low-alloy, 0.2% C steel.

Practice Problems: CCT Diagrams

- Conceptual Questions:

1. How is a CCT diagram different from a TTT diagram?
2. Why is a CCT diagram more useful than TTT for heat treating large components?

- Problem Examples:

3. Given a CCT diagram for eutectoid steel, sketch the cooling curve of a component air cooled vs. oil quenched.
   Q: What microstructures are expected in each case?
4. Given the CCT diagram for 1045 steel, find the minimum cooling rate required to obtain 90% martensite.

Industrial Case Study: Soft core in thick steel sections

Case: Large shafts hardened on surface but soft at the core.

Cause: Cooling rate in core too slow; bainite/pearlite formed.

Lesson: CCT diagrams predict *real industrial cooling behavior*.

Effect of Alloying Elements on Heat Treatment

Introduction to Alloying Elements in Steel

Alloying elements are added to steel to modify its mechanical properties, improve corrosion resistance, enhance hardenability, and control transformation behaviors during heat treatment. Each element has specific effects on phase stability and transformation kinetics.

Key Alloying Elements and Their Effects

- Chromium (Cr): Increases hardenability, corrosion resistance, and wear resistance.

- Nickel (Ni): Enhances toughness and impact strength, stabilizes austenite.

- Molybdenum (Mo): Improves hardenability and resistance to softening during tempering.

- Manganese (Mn): Improves hardenability and tensile strength.

- Silicon (Si): Promotes ferrite formation and improves magnetic properties.

- Vanadium (V): Refines grain structure, forms stable carbides, and increases strength.

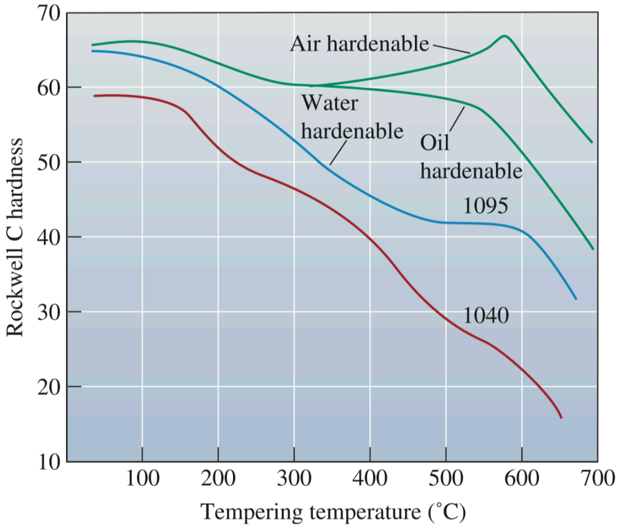
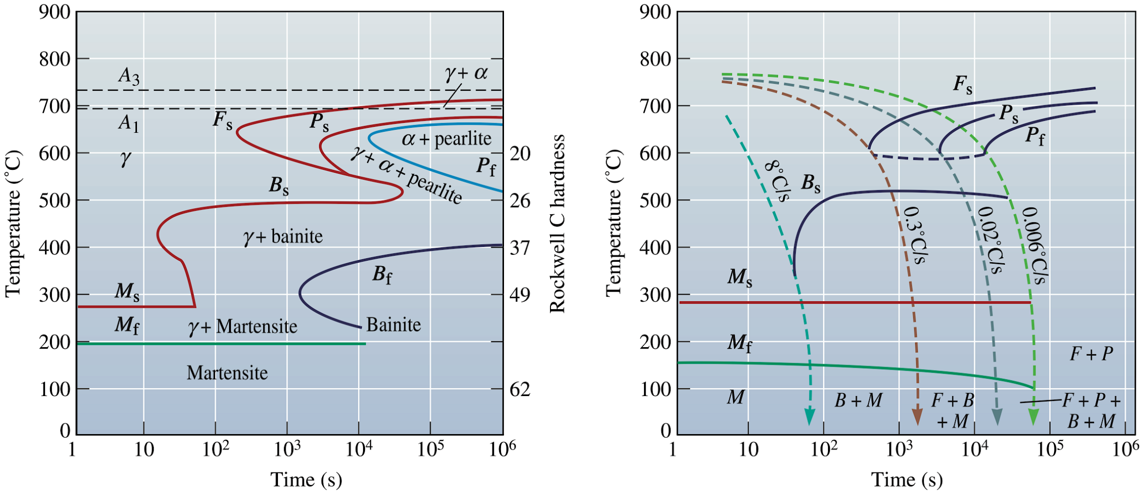


Figure 1. The effect of alloying elements on the phases formed during the tempering of steels. The air-hardenable steel shows a **secondary hardening peak**. (Adapted from Askeland & Wright, 2016).

Effect on TTT and CCT Diagrams

Alloying elements shift the TTT and CCT curves to the right, indicating slower transformation kinetics. This improves hardenability and allows for slower quenching rates to form martensite.



(a)

(b)

Figure 2. (a) TTT and (b) CCT curves for a 4340 steel.

Practical Implications in Heat Treatment

Steels with alloying elements require different heat treatment schedules compared to plain carbon steels. They can be quenched in oil or air while still forming martensite, reducing cracking risk. Alloying elements also influence tempering behavior and secondary hardness response.