FERROUS METALS AND ALLOYS

Chapter 6
6.1 Introduction to History-Dependent Materials

- The final properties of a material are dependent on their past processing history.
- Prior processing can significantly influence the final properties of a product.
- Ferrous (iron-based) metals and alloys were the foundation for the Industrial Revolution and are the backbone of modern civilization.
- There has been significant advances in the steel industry in the last ten years.
  - Over 50% of the steels made today did not exist ten years ago.
6.2 Ferrous Metals

- All steel is recyclable
- Recycling does not result in a loss of material quality
- Steel is magnetic which allows for easy separation and recycling
- 71% recycling rate for steel in the United States
Classification of Common Ferrous Metals and Alloys

Figure 6-1 Classification of common ferrous metals and alloys.
6.3 Iron

- Iron is the most important of the engineering metals
- Four most plentiful element in the earth’s crust
- Occurs in a variety of mineral compounds known as ores
- Metallic iron is made from processing the ore
  - Breaks the iron-oxygen bonds
  - Ore, limestone, coke (carbon), and air are continuously inputted into a furnace and molten metal is extracted
  - Results in pig iron
- A small portion of pig iron is cast directly; classified as cast iron
6.4 Steel

- Offers strength, rigidity, durability
- Construction and the automotive industries consume the most steel
- Steel is manufactured by an oxidation process that decreases the amount of carbon, silicon, manganese, phosphorous, and sulfur in pig iron or steel scrap
  - Kelly-Bessemer process
  - Open-hearth process
Solidification Concerns

- Steel must undergo a change from liquid to solid regardless of how it is processed
- Continuous casting produces the feedstock material that is used in forging or rolling operations
- Molten metal is poured into ladles
- Ladle metallurgy
  - Processes designed to provide final purification
  - Alloy additions
  - Dissolved gases can be reduced or removed
  - Grain size can be refined
- Processed liquid is often poured into a continuous caster
**Figure 6-3** a) Schematic representation of the continuous casting process for producing billets, slabs, and bars. (Courtesy of Materials Engineering, Penton Publishing, New York, NY.)
Deoxidation

• Steel may have large amounts of oxygen dissolved in the molten metal
• Solubility decreases during subsequent cooling and solidification
  – Oxygen and other gases are rejected
    • May become trapped and form bubbles
• Defects may be in the final product
• Porosity problems can be avoided if the oxygen is removed prior to solidification
  – The oxygen can also be reacted with other materials that have a higher affinity for oxygen than steel
  – Called deoxidizers
Degassification

- In vacuum degassing, a stream of molten metal passes through a vacuum chamber into a mold

- Consumable-electrode remelting
  - High surface area allows for degassing
  - Vacuum arc remelting (VAR)
  - Vacuum induction melting (VIM)
  - Fails to remove nonmetal impurities
Degassification Models

Figure 6-5 Method of degassing steel by pouring through a vacuum.

Figure 6-6b Schematic representation of this process showing the starting electrode, melting arc, and resolidified ingot. (Courtesy of Carpenter Technology Corporation, Reading, PA.)
Plain Carbon Steel

• Theoretically, steel is an alloy of only iron and carbon, but steel contains other elements in detectable amounts

• Plain carbon steel is when these elements are present, but not in any specified amount

• Strength is primarily a function of carbon content
Types of Carbon Steels

- **Low-carbon steels** have less than 0.20% carbon and have good formability.
- **Medium-carbon steels** have between 0.20% and 0.50% carbon:
  - Best balance of properties
  - High toughness and ductility are good with respect to the levels of strength and hardness.
- **High-carbon steels** have more than 0.50% carbon:
  - Toughness and formability are low, but hardness and wear resistance are high.
- **Carbon steels** have high strength, high stiffness, and reasonable toughness:
  - Rust easily and require surface protection.
Different Classes of Carbon Steels

**TABLE 6-1** Effect of Carbon on the Strength of Annealed Plain-Carbon Steels

<table>
<thead>
<tr>
<th>Type of Steel</th>
<th>Carbon Content</th>
<th>Minimum Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1020</td>
<td>0.20%</td>
<td>414 Mpa 60 ksi</td>
</tr>
<tr>
<td>1030</td>
<td>0.30%</td>
<td>448 Mpa 65 ksi</td>
</tr>
<tr>
<td>1040</td>
<td>0.40%</td>
<td>517 Mpa 75 ksi</td>
</tr>
<tr>
<td>1050</td>
<td>0.50%</td>
<td>621 Mpa 90 ksi</td>
</tr>
</tbody>
</table>

*Data are from ASTM Specification A732.*

**Figure 6-7** A comparison of low-carbon, medium-carbon, and high-carbon steels in terms of their relative balance properties. a) Low-carbon steel has excellent ductility and fracture resistance, but lower strength; b) medium-carbon steel has balanced properties; c) high-carbon steel has high strength and hardness at the expense of ductility and fracture resistance.
Alloy Steels

- Steels containing alloys in specifiable amounts
  - 1.65% or more manganese
  - 0.60% silicon
  - 0.60% copper

- Most common alloying elements are chromium, nickel, molybdenum, vanadium, tungsten, cobalt, boron and copper

- Low alloy steels contain less than 8% alloy additions

- High alloy steels contain more than 8% alloy additions
Effects of Alloying Elements

**TABLE 6-3** Principal Effects of Major Alloying Elements in Steel

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
<th>Primary Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.95–1.30</td>
<td>Alloying element in nitriding steels</td>
</tr>
<tr>
<td>Bismuth</td>
<td>—</td>
<td>Improves machinability</td>
</tr>
<tr>
<td>Boron</td>
<td>0.001–0.003</td>
<td>Powerful hardenability agent</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.5–2</td>
<td>Increase of hardenability</td>
</tr>
<tr>
<td></td>
<td>4–18</td>
<td>Corrosion resistance</td>
</tr>
<tr>
<td>Copper</td>
<td>0.1–0.4</td>
<td>Corrosion resistance</td>
</tr>
<tr>
<td>Lead</td>
<td>—</td>
<td>Improved machinability</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.25–0.40</td>
<td>Combines with sulfur to prevent brittleness</td>
</tr>
<tr>
<td></td>
<td>&gt;1</td>
<td>Increases hardenability by lowering transformation points and causing transformations to be sluggish</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.2–5</td>
<td>Stable carbides; inhibits grain growth</td>
</tr>
<tr>
<td>Nickel</td>
<td>2–5</td>
<td>Toughener</td>
</tr>
<tr>
<td></td>
<td>12–20</td>
<td>Corrosion resistance</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.2–0.7</td>
<td>Increases strength</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Spring steels</td>
</tr>
<tr>
<td></td>
<td>Higher percentages</td>
<td>Improves magnetic properties</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.08–0.15</td>
<td>Free-machining properties</td>
</tr>
<tr>
<td>Titanium</td>
<td>—</td>
<td>Fixes carbon in inert particles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduces martensitic hardness in chromium steels</td>
</tr>
<tr>
<td>Tungsten</td>
<td>—</td>
<td>Hardness at high temperatures</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.15</td>
<td>Stable carbides; increases strength while retaining ductility, promotes fine grain structure</td>
</tr>
</tbody>
</table>
AISI-SAE Classification System

- Classifies the alloys by chemistry
- Society of Automotive Engineers (SAE) and the American Iron and Steel Institute (AISI) have developed systems for classifying steel
- Incorporated into the Universal Numbering System
- First number indicates the major alloying elements
- Second number designates a subgrouping within the major alloy system
- Last two digits indicate the carbon percentage
# AISI-SAE Classification System

<table>
<thead>
<tr>
<th>AISI Number</th>
<th>Type</th>
<th>Mn (%)</th>
<th>Ni (%)</th>
<th>Cr (%)</th>
<th>Mo (%)</th>
<th>V (%)</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>Carbon steels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10xx</td>
<td>Plain carbon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11xx</td>
<td>Free cutting (S)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12xx</td>
<td>Free cutting (S) and (P)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15xx</td>
<td>High manganese</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13xx</td>
<td>High manganese</td>
<td>1.60–1.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2xxx</td>
<td>Nickel steels</td>
<td>3.5–5.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3xxx</td>
<td>Nickel–chromium</td>
<td>1.0–3.5</td>
<td>0.5–1.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4xxx</td>
<td>Molydenum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40xx</td>
<td>Mo</td>
<td></td>
<td></td>
<td></td>
<td>0.15–0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41xx</td>
<td>Mo,Cr</td>
<td>0.40–1.10</td>
<td>0.08–0.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43xx</td>
<td>Mo,Cr,Ni</td>
<td>1.65–2.00</td>
<td>0.40–0.90</td>
<td>0.20–0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44xx</td>
<td>Mo</td>
<td></td>
<td></td>
<td></td>
<td>0.35–0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46xx</td>
<td>Mo,Ni (low)</td>
<td>0.70–2.00</td>
<td>0.15–0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47xx</td>
<td>Mo,Cr,Ni</td>
<td>0.90–1.20</td>
<td>0.35–0.55</td>
<td>0.15–0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48xx</td>
<td>Mo,Ni (high)</td>
<td>3.25–3.75</td>
<td>0.20–0.30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5xxx</td>
<td>Chromium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.20–0.60</td>
<td></td>
</tr>
<tr>
<td>51xx</td>
<td>Chromium–vanadium</td>
<td></td>
<td>0.70–1.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6xxx</td>
<td>Chromium–vanadium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.50–1.10</td>
<td>0.10–0.15</td>
</tr>
<tr>
<td>61xx</td>
<td>Ni,Cr,Mo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8xxx</td>
<td>Ni,Cr,Mo</td>
<td>0.20–0.40</td>
<td>0.30–0.55</td>
<td>0.08–0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>81xx</td>
<td></td>
<td>0.40–0.70</td>
<td>0.40–0.60</td>
<td>0.15–0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>86xx</td>
<td></td>
<td>0.40–0.70</td>
<td>0.40–0.60</td>
<td>0.20–0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>87xx</td>
<td></td>
<td>0.40–0.70</td>
<td>0.40–0.60</td>
<td>0.30–0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>88xx</td>
<td></td>
<td>0.40–0.70</td>
<td>0.40–0.60</td>
<td>0.30–0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9xxx</td>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>92xx</td>
<td>High silicon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.20–2.20S</td>
</tr>
<tr>
<td>93xx</td>
<td>Ni,Cr,Mo</td>
<td>3.00–3.50</td>
<td>1.00–1.40</td>
<td>0.08–0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>94xx</td>
<td>Ni,Cr,Mo</td>
<td>0.30–0.60</td>
<td>0.30–0.50</td>
<td>0.08–0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Other Designations

• Letters may be used in the AISI-SAE systems
  – B- addition of boron
  – L- lead addition
  – E- electric furnace process

• American Society for Testing Materials (ASTM) and the U.S. government have specifications based on the application
Selecting Alloy Steels

• Two or more alloying elements can produce similar effects
• Typically, the least expensive alloy is selected
• Important to consider both use and fabrication
  – Define required properties
  – Determine the best microstructure
  – Determine method of product or part
  – Select the steel with the best carbon content and hardenability
High-Strength Low-Alloy Structural Steels

• Two general categories of alloy steels
  – Constructional alloys
  – High-strength low-alloy (HSLA)
    • Provide increased strength to weight ratio
    • Modest increase in cost
    • Available in sheet, strip, plate, structural shapes, and bars
    • High yield strength, good weldability, and good corrosion resistance
Relationships Between Mechanical Properties and Heat-Treated Steels

Figure 6-8 Relationships between the mechanical properties of a variety of properly heat-treated AISI-SAE alloy steels. (Courtesy of ASM International, Materials Park, OH.)
Typical Compositions and Properties of HSLA

<table>
<thead>
<tr>
<th>Group</th>
<th>Chemical Compositions(^a) (%)</th>
<th>Strength Properties</th>
<th>Elongation in 2 in. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>Si</td>
</tr>
<tr>
<td>Columbium or vanadium</td>
<td>0.20</td>
<td>1.25</td>
<td>0.30</td>
</tr>
<tr>
<td>Low manganese–vanadium</td>
<td>0.10</td>
<td>0.50</td>
<td>0.10</td>
</tr>
<tr>
<td>Manganese–copper</td>
<td>0.25</td>
<td>1.20</td>
<td>0.30</td>
</tr>
<tr>
<td>Manganese–vanadium–copper</td>
<td>0.22</td>
<td>1.25</td>
<td>0.30</td>
</tr>
</tbody>
</table>

\(^a\) All have 0.04% P, 0.05% S, and 0.20% Cu.
Microalloyed Steels in Manufactured Products

- Microalloyed steels are between carbon steels and alloy grades with respect to cost and performance
- These steels offer maximum strength with minimum carbon
- Preserves weldability, machinability, and formability
- Energy savings can be substantial
Bake-Hardenable Steel

- Resistant to aging during normal storage
- Age during sheet metal forming
- Increase in strength occurs after the forming operations
- Material offers good formability
- Improved dent resistance
Advanced High-Strength Steels (AHSS)

- Enable the stamping or hydroforming of complex parts
- Higher strength provides improved fatigue resistance
- Possibility of weight reduction
- Dual-phase steels can absorb more energy, meaning they are better for crash resistance in automotive applications
- Transformation-induced plasticity (TRIP)
  - Excellent energy absorption during crash deformation
- Complex-phase (CP) has high strength
Free-Machining Steels

• Machine readily and form small chips when cut
• The smaller the chips reduce friction on the cutting tool which reduces the amount of energy required
  – Reduces tool wear
• Additions provide built-in lubrications
  – Lead
  – Bismuth
    • more environmentally friendly
• Ductility and impact properties are reduced
Precoated Steel Sheet

- Typical sheet metal processes shape bare steel followed by finishing
- Precoated steel sheets can also be formed
  - Eliminates the post processing finishing operations
- Dipped, plated, vinyls, paints, primers and polymer coatings can be used
Steels for Electrical and Magnetic Applications

• Soft magnetic materials can be magnetized by low-strength magnetic fields
  – Lose almost all of their magnetism when the field is removed
  – Products such as solenoids, transformers, generators, and motors

• Amorphous metals
  – No crystal structure, grains, or grain boundaries
  – Magnetic domains can move freely
  – Properties are the same in all directions
  – Corrosion resistance is improved
Special Steels

• Maraging steels
  – Used when extremely high strength is required
  – Typically also have high toughness

• Steels for High-Temperature Service
  – Plain-carbon steels should not be used for temperatures in excess of 250°C
  – Tend to be low-carbon materials
6.6 Stainless Steels

• Chromium additions provide
  – Improved corrosion resistance
  – Outstanding appearance

• Tough, corrosion-resistant oxide layer can heal itself if oxygen is present
  – Materials that have this corrosion resistant layer are said to be true stainless steels

• Designations for stainless steels are based on their microstructures
### Designations for Stainless Steels

#### TABLE 6-6  AISI Designation Scheme for Stainless Steels

<table>
<thead>
<tr>
<th>Series</th>
<th>Alloys</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>Chromium, nickel, manganese, or nitrogen</td>
<td>Austenitic</td>
</tr>
<tr>
<td>300</td>
<td>Chromium and nickel</td>
<td>Austenitic</td>
</tr>
<tr>
<td>400</td>
<td>Chromium and possibly carbon</td>
<td>Ferritic or martensitic</td>
</tr>
<tr>
<td>500</td>
<td>Low chromium (&lt;12%) and possibly carbon</td>
<td>Martensitic</td>
</tr>
</tbody>
</table>

#### TABLE 6-7  Primary Strengthening Mechanism for the Various Types of Stainless Steel

<table>
<thead>
<tr>
<th>Type of Stainless Steel</th>
<th>Primary Strengthening Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferritic</td>
<td>Solid-solution strengthening</td>
</tr>
<tr>
<td>Martensitic</td>
<td>Phase transformation strengthening (martensite)</td>
</tr>
<tr>
<td>Austenitic</td>
<td>Cold work (deformation strengthening)</td>
</tr>
</tbody>
</table>
Microstructures for Stainless Steel

• Ferritic stainless steel
  – Corrosion resistant iron alloy with sufficient chromium and low carbon content that is ferrite at all temperatures
  – Limited ductility
  – Poor toughness
  – Readily weldable
  – Cheapest

• Martensitic stainless steels
  – Increased strength
  – More carbon content, less chromium
  – Less corrosion resistant than ferritic
  – More expensive than ferritic
Microstructures for Stainless Steel

- Austenitic stainless steels
  - Costs two to three times as much as the ferritic alloys
  - Nonmagnetic structure
  - High corrosion resistance
  - May be polished to a mirror finish
  - Good formability
  - Increased strength

- Precipitation-hardening variety
  - Addition of alloying elements to increase strength

- Free-machining stainless steels
  - Addition of sulfur
## Popular Stainless Steels

<table>
<thead>
<tr>
<th>AISI type</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martensitic 410</td>
<td>General purpose</td>
</tr>
<tr>
<td>(hardenable by heat treatment) 420</td>
<td>Hardenable by heat treatment</td>
</tr>
<tr>
<td>440C</td>
<td>Hardenable by heat treatment</td>
</tr>
<tr>
<td>Ferritic 405</td>
<td>Hardenable by cold working</td>
</tr>
<tr>
<td>(more corrosion resistant than martensitic, but not hardenable by heat treatment) 430</td>
<td>Hardenable by cold working</td>
</tr>
<tr>
<td>446</td>
<td>Hardenable by cold working</td>
</tr>
<tr>
<td>Austenitic 201</td>
<td>For elevated-temperature service</td>
</tr>
<tr>
<td>(best corrosion resistance, but hardenable only by cold working) 202</td>
<td>For elevated-temperature service</td>
</tr>
<tr>
<td>301</td>
<td>Modified for welding</td>
</tr>
<tr>
<td>302</td>
<td>Superior corrosion resistance</td>
</tr>
<tr>
<td>302B</td>
<td>Superior corrosion resistance</td>
</tr>
<tr>
<td>304L</td>
<td>Superior corrosion resistance</td>
</tr>
<tr>
<td>310</td>
<td>Superior corrosion resistance</td>
</tr>
<tr>
<td>316</td>
<td>Superior corrosion resistance</td>
</tr>
<tr>
<td>321</td>
<td>Superior corrosion resistance</td>
</tr>
</tbody>
</table>

**Figure 6-10** Popular alloys and key properties for different types of stainless steels.
6.6 Tool Steels

- High carbon, high strength, ferrous alloys that have a balance of strength, toughness, and wear resistance

- Types of tool steels
  - Water-hardening tool steels (W)
    - Least expensive method for small parts that are not subjected to extreme temperatures
  - Cold-work steels (O,A)
    - Larger parts that must be hardened
    - Oil or air quenched grades
Types of Tool Steels

• Shock resisting tool steels (S)
  – Offers high toughness for impact applications

• High speed tool steels
  – Used for cutting tools where strength and hardness are needed at high temperatures

• Hot-work steels (H)
  – Provide strength and hardness during high temperature applications

• Plastic mold steels (P)
  – Meets requirements of zinc die and plastic injection molding

• Special purpose tool steels (L,F)
  – Extreme toughness, extreme wear resistance
6.7 Alloy Cast Steels and Irons

- Ferrous casting alloys are classified by their carbon content
  - Less than 2.0% = cast steel
  - More than 2.0% = cast iron
- Only heat treatments are stress relief or annealing
- Alloying elements are selected to alter properties
  - Affect the formation of graphite or cementite
  - Modify the morphology of the carbon-rich phase
  - Strengthen the matrix
  - Enhance wear resistance
Cast Alloys

• High-alloy cast irons
  – Provide enhanced corrosion resistance
  – Suitable for elevated temperature applications
• SAE and ASTM have specifications for grades of cast alloys
• Cast steels are used whenever a cast iron is not adequate
• Cast steels are stiffer, tougher, and more ductile over a wider temperature range
• Cast steels are easily welded, but have a higher melting point, less fluidity, and increased shrinkage
Summary

• The processing of steels determines the final material properties
• Steel’s typically have high strength, rigidity, and durability
• Steel is recyclable
• Different alloying elements may be added to produce known effects to the material
• Stainless steels are a commonly used steel that have good corrosion resistance
Materials Properties

- STRUCTURE
- PERFORMANCE
- PROCESSING
- PROPERTIES
5.1 Structure – Property Relationships

- Properties and structure can be manipulated and controlled
- Interactive relation to yield improved materials engineering solutions
5.1 What is a Heat Treatment?

- **Heat treatment** is defined as controlled heating and cooling of materials for the purpose of altering their structures and properties.
- Changes in properties can be introduced with no change in shape.
- Heat treatment-term- applies only for processes where heating & cooling are performed intentionally for the purpose of altering properties (not as a side-effect due to environmental/application conditions-such as hot forming or welding).
5.1 Introduction

• Heat treatments are integrated with other processes to obtain effective results
• 90% of heat treatments performed on steel and other ferrous alloys
5.2 Processing Heat Treatments

• Most heat treatments are thermal processes that increase strength
• Processing heat treatments are used to prepare the material for fabrication
• Equilibrium phase diagrams are often used to predict resulting structures
• Annealing is a common heat treatment process
  – May be used to reduce strength and hardness
  – Removes residual stresses
  – Improves toughness
  – Restores ductility
  – Refines grain size
5.2 Eutectoid Transformation of Steel

- Simplified Iron-Carbon phase diagram:

![Iron-Carbon phase diagram](image)
5.2 Process Heat Treatments

[Diagram showing heat treatment processes with temperature and carbon content axes, labeled Normalizing, Full annealing and hardening, Spheroidizing anneal, Process anneal, and a phase diagram with A_{cm}, A_3, and A_1 lines.]
5.2 Annealing

• Full Annealing
  – **Hypoeutectoid** steels are heated to convert the grain structure to homogenous single phase **austenite**, then control cooled (the cooling results in coarse **pearlite** with **excess ferrite** resulting in soft and ductile steel)

  – **Hypereutectoid** steels undergo a similar process but the structure will be **coarse perlite** with **excess cementite**

  – Full anneals are time and energy consuming processes
5.2 Normalizing

• Normalizing is heating steel to a temperature higher than in annealing (60°C above line A3 for hypo-eutectoid)
  – More cost effective than annealing
  – Cooled in air

• Normalizing vs. annealing
  – In normalizing, cooling will be different in different locations
  – Properties will vary between the surface and interior in normalized steel
  – Lower cost of normalizing is justified if uniform properties are not needed
5.2 Process Anneal

• Steel is heated to a temperature slightly below A1
• Held long enough to attain recrystallization with no phase change
• Recrystallization is induced after a material has been cold worked to reduce strain
5.2 Spheroidizing Annealing

- Applied to high-carbon (0.6% C) steel
- Heated below A1
- Cementite form globules throughout a ferrite matrix
5.2 Stress-relief Anneal

- Reduces residual stresses in casting, welded assemblies, and cold-formed products
- Materials are heated and then slowly cooled
5.2 Normalizing

- Carbon steel is heated to approximately 55 °C above A3 or Acm for 1 hour;
- The steel completely transforms to austenite;
- The steel is then air-cooled, which is a cooling rate of approximately 38 °C (100 °F) per minute;
- This results in a fine pearlitic uniform structure, and a more-structure;
- Normalized steel has a higher strength than annealed steel;
- It has a relatively high strength and ductility.
5.3 Heat Treatments Used to Increase Strength

• Six mechanisms for increasing strength
  – Solid-solution strengthening
    • Base metal dissolves other atoms as substitutional solutions or interstitial solutions
  – Strain hardening
    • Increases strength by plastic deformation
  – Grain size refinement
    • Metals with smaller grains tend to be stronger
  – Precipitation hardening
    • Strength is obtained from a nonequilibrium structure
  – Dispersion hardening
    • Dispersing second-phase particles through a base material
  – Phase transformations
    • Heated to form a single phase at an elevated temperature
Heat Treatments for Nonferrous Metals

• Nonferrous metals do not have significant phase transitions

• Heat treated for three purposes
  – Produce a uniform, homogenous structure
  – Provide a stress relief
  – Induce recrystallization

• In castings that have been cooled too rapidly, homogenization can be achieved by heating to moderate temperatures and then holding
5.4 Strengthening Heat Treatments for Nonferrous Metals

• Precipitation hardening is the most effective mechanism to strengthen nonferrous metals
  – Alloys must exhibit solubility that decreases with decreasing temperature

• When two or more phases exist, the material is dispersion strengthened

• Dislocations can also provide strength

• Precipitation hardening process
  – Heating, quenching, aging
5.4 Precipitation or Age Hardening

- High-Al section of Al-Cu equilibrium diagram
5.4 Iron-Thermal Treatment of Al-Cu Alloy
Coherency

- Solute atoms distort or strain lattices
- If the strain exceeds a certain point, the solute atoms can break free and form their own crystal structure
  - Dispersion strengthening
  - Strength and hardness decrease and the material is said to be overaged

**Figure 5-5** Two dimensional illustrations depicting a) a coherent precipitate cluster where the precipitate atoms are larger than those in the host structure, and b) its companion overaged or discrete second phase precipitate particle. Parts c) and d) show equivalent sketches where the precipitate atoms are smaller than the host.
Aging Curves

Figure 5-6 Aging curves for the Al-4%Cu alloy at various temperatures showing peak strengths and times of attainment. (Adapted from Journal of the Institute of Metals, Vol. 79, p. 321, 1951.)
5.5 Strengthening Heat Treatments for Steel

- Steel is the most common material to be heat treated
- Isothermal transformation (I-T) or time-temperature-transformation (T-T-T) diagrams are used to understand the process
- Phase transformations are most rapid at an intermediate temperature
  - C-structure represents this phenomenon
Figure 5-7 Isothermal transformation diagram (T-T-T diagram) for eutectoid composition steel. Structures resulting from transformation at various temperatures are shown as insets. (Courtesy of United States Steel Corp., Pittsburgh, PA.)
5.5 CCT of Steel
5.5 Tempering

- This is the most common heat treatment
- Involves reheating quenched steel to a temperature below the eutectoid temperature then cooling.
- The elevated temperature allows very small amounts of spheroidite to form
- This restores ductility, but reduces hardness.
5.5 Martensite Transformation

- Carbon steel with at least 0.4 wt% C is heated to normalizing temperatures and then rapidly cooled (quenched) in water, brine, or oil to the critical temperature.
- The critical temperature is dependent on the carbon content, but as a general rule is lower as the carbon content increases.
- The steel possesses a super-saturated carbon content.
- The steel is extremely hard but brittle, usually too brittle for practical purposes.
- The internal stresses cause stress cracks on the surface.
5.5 Tempering of Martensite

- Initially after it has been quenched, martensite lacks the toughness and ductility for engineering applications.
- Tempering is a subsequent heating to give the steel necessary ductility and fracture toughness.

Photomicrograph of martensite 1000X
5.5 Recrystalized Oxidized Fragment

- Left: heavily deformed and recrystalized regions, 500X
- Right: recovered oxidized fragment (t=390 deg C)
5.5 Maraging Steels

- **Maraging steels** (a portmanteau of martensitic and aging) are iron alloys which are known for possessing superior strength and toughness without losing malleability.
- A special class of low carbon ultra-high strength steels which derive their strength not from carbon, but from precipitation of inter-metallic compounds.
- The principal alloying element is 15 to 25% nickel.[1]
- Secondary alloying elements are added to produce intermetallic precipitates, which include cobalt, molybdenum, and titanium.[1]
- Original development was carried out on 20 and 25% Ni steels to which small additions of Al, Ti, and Nb were made.
Additional Heat Treatments

• Process anneal
  – Recrystallization is induced after a material has been cold worked to reduce strain hardening effects
  – Induces a change in size, shape, and distribution

• Stress-relief anneal
  – Reduces residual stresses in casting, welded assemblies, and cold-formed products
  – Materials are heated and then slow cooled

• Spheroidization
  – Objective is to produce a structure in which all of the cementite is in the form of small spheroids or globules dispersed throughout a ferrite matrix
Martensite

- If excess carbon becomes trapped in the microstructure, it becomes a distorted BCC structure.
- This new structure is known as martensite.
- The hardness and strength of steel with martensitic structure are strong functions of the carbon content.
- The amount of martensite that forms is not a function of time, but the temperature during quenching.

Figure 5-9 Effect of carbon on the hardness of martensite.
Tempering of Martensite

• Initially after it has been quenched, martensite lacks the toughness and ductility for engineering applications.

• Tempering is a subsequent heating to give the steel necessary ductility and fracture toughness.
## Tempering of Martensite

<table>
<thead>
<tr>
<th>Heat Treatment</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age hardening</td>
<td><strong>Solution treatment.</strong> Heat into the stable single-phase region (above the solvus) and hold to form a uniform-chemistry single-phase solid solution.</td>
<td><strong>Quench.</strong> Rapid cool to form a nonequilibrium supersaturated single-phase solid solution (crystal structure remains unchanged, material is soft and ductile).</td>
<td><strong>Age.</strong> A controlled reheat in the stable two-phase region (below the solvus). The material moves toward the formation of the stable two-phase structure, becoming stronger and harder. The properties can be “frozen in” by dropping the temperature to stop further diffusion.</td>
</tr>
<tr>
<td>Quench and temper for steel</td>
<td><strong>Austenitize.</strong> Heat into the stable single-phase region (above the (A_3) or (A_{cm})) and hold to form a uniform-chemistry single-phase solid solution (austenite).</td>
<td><strong>Quench.</strong> Rapid cool to form a nonequilibrium supersaturated single-phase solid solution (crystal structure changes to body-centered martensite, which is hard but brittle).</td>
<td><strong>Temper.</strong> A controlled reheat in the stable two-phase region (below the (A_1)). The material moves toward the formation of the stable two-phase structure, becoming weaker but tougher. The properties can be “frozen in” by dropping the temperature to stop further diffusion.</td>
</tr>
</tbody>
</table>
Properties of Processed Steel

Figure 5-13 Properties of an AISI 4140 steel that has been austenitized, oil-quenched, and tempered at various temperatures. (Adapted from Engineering Properties of Steel, ASM International, Materials Park, OH., 1982.)
Continuous Cooling Transformations

• TTT curves assume that the properties of instantaneous heating followed by constant temperature transformation match reality

• Continuous cooling transformations (CCT) diagrams show a more accurate picture of the transformations

Figure 5-14 C-C-T diagram for a eutectoid composition steel (bold), with several superimposed cooling curves and the resultant structures. The lighter curves are the T-T-T transitions for the same steel. (Courtesy of United States Steel Corp., Pittsburgh, PA.)
Jominy Test for Hardenability

- Material + cooling rate → structure → properties
- A heated material is quenched from one end
- Standards for Jominy test
  - Quench medium
  - Internal nozzle diameter
  - Water pressure
- All cooling is along the axis of the bar
- After the bar is cooled, Rockwell hardness readings are taken (i.e. strength)
Jominy Hardness Test

**Figure 5-15** Schematic diagram of the Jominy hardenability test.

**Figure 5-16** Typical hardness distribution along a Jominy test specimen.
Hardenability Considerations

- Hardness is a material property that is related to strength
  - Strong function of the carbon content and microstructure
- Hardenability measures the ability of a material to be fully hardened under normal hardening cycles
  - Related to the amounts and types of alloying elements
- Primary reason to add an alloying element is to increase hardenability
- The greater a material’s hardenability, the easier it is for a material to be slow cooled
  - Slow cooling reduces the probability of quench-cracking
Quench Media

• Quenchants are the medium in which a material is quenched
  – Selected to provide necessary cooling rates

• Stages of quenching
  – Formation of the vapor jacket
    • Vapor jacket is the thin gaseous layer between the metal and the liquid during cooling
  – Nucleate boiling phase
    • Produces rapid rates of cooling down to the boiling point of the quenchant
  – Conduction and convection
    • Slower cooling from the boiling point to room temperature
Quenching Considerations

• Water is an effective quenching medium because of its high heat of vaporization and relatively high boiling point
  – The quenchant should be agitated due to the tendency of bubbles to form soft spots on the metal
  – A negative consequence is that it may oxidize the material

• Brine is similar to water as a quenchant medium
  – Rapid cooling occurs because the salt nucleates bubbles
  – Corrosion problems may exist
Quenching Considerations

• Oil is utilized if slower quenching rates are desired
  – Oil may cause water contamination, smoke, fumes, etc.
  – More expensive than water or brine quenchants
• Water based polymer quenchants have properties between oil and water and brine
• Molten salt baths may be used for even slower cooling rates
• High pressure quenching uses a stream of flowing gas to extract heat
Design Concerns, Residual Stresses, Distortion, and Cracking

- Product and design and material selection play an important role in proper heat treatment of parts.
- Residual stresses are stresses that exist in a part independent of an applied stress.
- Most parts being heat treated experience nonuniform temperatures during cooling or quenching.
Figure 5-19 Three-layer model of a plate undergoing cooling. The upper sequence depicts a material such as aluminum that contracts upon cooling while the bottom sequence depicts steel, which expands during the cooling-induced phase transformation.
Design Considerations

• Ways to prevent quench cracking and residual stresses
  – More uniform cross-sectional area
  – Generous fillets
  – Radiused corners
  – Smooth transitions
  – Adding additional holes

• Residual stresses can accelerate corrosion problems

Figure 5-20 a) Shape containing nonuniform sections and a sharp interior corner that may crack during quenching. This is improved by using a large radius to join the sections. b) Original design containing sharp corner holes, which can be further modified to produce more uniform sections.
Techniques to Reduce Cracking and Distortion

• Rapid cools may be used to prevent pearlite transformation
  – Instead of quenching in a liquid medium, the metal is quenched in a hot oil or molten salt bath to allow the entire piece to return to a nearly uniform temperature
  – If the metal is held at this temperature for enough time, the austenite will turn to bainite
• Process is known as austempering
  – If the metal is brought to a uniform temperature and then slow cooled through martensite transformation, the process is known as martempering
Ausforming

• Commonly confused with austempering
• Material is heated to form austenite and then quenched to a temperature between pearlite and bainite
• Increased ductility
• Finer grain size
• Some degree of strain hardening
5.6 Surface Hardening of Steel

- Methods to produce properties that vary throughout the material
  - Selective heating of the surface
  - Altered surface chemistry
  - Deposition of an additional surface layer
  - Section of gear teeth showing induction hardened surfaces (Figure)
Selective Heating Techniques

- Surface properties are established by surface treatments
  - Flame hardening
    - Uses an oxy-acetylene flame to raise the surface temperature to reform austenite
    - Surface is then water quenched to form martensite
    - Tempered to a desired hardness
  - Induction hardening
    - Steel part is placed inside a conductor coil and alternating current is used to change the surface of the steel
    - Rate and depth of heating can be controlled
    - Ideal for round bars and cylindrical parts
Selective Heating Techniques

• Laser beam hardening
  – Produces hardened surfaces
  – Absorptive coatings (zinc or manganese phosphate) are applied to the steel to increase efficiency
  – Beam size, beam intensity, and scanning speed are adjustable to affect the depth of heating

• Electron beam hardening
  – Similar to laser beam hardening
  – Heat source is a beam of high-energy electrons
Techniques Involving Altered Surface Chemistry

• Carburizing is the diffusion of carbon into FCC, austenite steel at elevated temperatures
  – In gas carburizing, a hot gas containing carbon surround the part
  – In pack carburizing, the steel is surrounded by a solid that contains carbon
  – In liquid carburizing, the steel is placed in a molten bath with carbon
Techniques Involving Altered Surface Chemistry

- Nitriding hardens the surfaces by producing alloy nitrides in special steels that contain nitride-forming elements
  - Aluminum, chromium, molybdenum, vanadium
- Ionitriding is a plasma process that places parts in an evacuated furnace and treats them with direct current potential
  - Low pressure nitrogen is then introduced into the furnace and becomes ionized
- Ion carburizing is similar to ionitriding except that methane is introduced instead of nitrogen
- Carbonitriding is where both nitrogen and carbon are introduced
5.7 Furnaces

• Furnace types
  – Parts remain stationary in batch furnaces
  – Continuous furnaces move the components through heat treating processes that are compatible with other manufacturing processes
  • Box furnaces are horizontal batch furnaces
  • Car-bottom-box furnaces are used for large and long workpieces
  – Bell furnaces place a “bell” over the workpiece to control heating and cooling
  • Elevator furnaces
  – Vertical pit furnaces prevent horizontal sagging or warping
Furnace Atmospheres

• Artificial gas atmospheres
  – Prevents scaling or tarnishing

• Fluidized-bed
  – Inert particles are heated and suspended in a stream of gas

• Salt bath furnaces
  – Salt is heated by passing a current between two electrodes placed in the batch
  – Lead pot is a bath where lead is used instead of salt

• Electrical induction heating
5.8 Heat Treatment and Energy

• Heat treatments can consume significant amounts of energy
  – High temperatures
  – Long heating times

• Manufacture of more durable products eliminates frequent replacements

• Higher strengths may allow for less material

• Industry is trying to reduce energy consumption, processing times, and emissions
Summary

• Heat treatments are used to control material properties
• Mechanical properties may be changed by changing the microstructure of the material
• T-T-T and C-C-T curves are used to understand the heat treating processes
• Selective heating may be used to only change properties of the material at certain points on the part