Metals and alloys have many useful engineering properties. Alloys based on iron are called **ferrous** alloys and those based on the other metals are called **nonferrous** alloys.

**The Iron – Iron Carbide Phase Diagram**

Plain carbon steels are iron carbon alloys containing from a very small amount (0.03%) to about 1.2% carbon, 0.25 to 1.00% manganese, and other minor amounts of other elements (e.g. sulphur, silicon, phosphorus). In this context, plain carbon steel encompasses the iron-carbon binary alloy which composes of up to 6.6% carbon. The phase diagram is shown in Figure 10.26.

![Iron–Iron Carbide Phase Diagram](image-url)
**Solid Phases in the Fe – Fe₃C Phase Diagram**

**α ferrite**
This phase is an interstitial solid solution of carbon in the BCC iron crystal lattice. As indicated by the Fe – Fe₃C phase diagram, carbon is only slightly soluble in ferrite, reaching maximum solid solubility of 0.02% at 723°C. The solubility of carbon in α ferrite decreases to 0.005% at 0°C.

**Austenite (γ)**
The interstitial solid solution of carbon in γ iron is called austenite. It has an FCC crystal structure and a much higher solid solubility for carbon than α ferrite. The solid solubility of carbon in austenite is a maximum of 2.08% at 1148°C and decreases to 0.8% at 723°C.

**Cementite (Fe₃C)**
The intermetallic compound Fe₃C is called cementite. Cementite has negligible solubility limits and a composition of 6.67% C and 93.3% Fe. Cementite is a hard and brittle compound.

**δ Ferrite**
The interstitial solid solution of carbon in iron is called δ ferrite. It has a BCC crystal structure like α ferrite but with a greater lattice constant. The maximum solid solubility of carbon is δ ferrite is 0.09% at 1465°C.
Invariant Reaction in the Fe – Fe3C Phase Diagrams

Peritectic reaction
At the peritectic reaction point, liquid of 0.53% C combines with δ ferrite of 0.09% C to form γ austenite of 0.217% C. This reaction occurs at 1493°C and can be written as

\[
\text{Liquid (0.52% C)} + \delta(0.09\% \text{ C}) \xrightarrow{1493\text{°C}} \gamma(0.17\% \text{ C})
\]

Eutectic reaction
At the eutectic reaction point, liquid of 4.3% forms γ austenite of 2.08% C and the intermetallic compound Fe₃C (cementite) which contains 6.67% C. This reaction which occurs at 1147°C can be written as

\[
\text{Liquid (4.3% C)} \xrightarrow{1147\text{°C}} \gamma(2.14\% \text{ C}) + \text{Fe₃C (6.7% C)}
\]
Eutectoid reaction

At the eutectoid reaction point, solid austenite of 0.8% C produces $\alpha$ ferrite with 0.02% C and Fe$_3$C (cementite) which contains 6.67% C. This reaction which occurs at 723°C can be written as

$$\gamma \text{ austenite (0.76 % C) } \rightarrow \alpha \text{ ferrite (0.022% C) + Fe}_3\text{C (6.7% C)}$$

Plain carbon steel which contains 0.76% C is called a eutectoid steel since an all-eutectoid structure of $\alpha$ ferrite and Fe$_3$C is formed when austenite of this composition is slowly cooled below the eutectoid temperature. If a plain-carbon steel contains less than 0.76% C, it is termed a hypoeutectoid steel and if the steel contains more that 0.76% C, it is termed a hypereutectoid steel.
Slow Cooling of Plain-Carbon Steels

Eutectoid steels

If a sample of a eutectoid steel is heated to about 750°C and held for a sufficient time, its structure will become homogeneous austenite. This process is called **austenitizing**.

If this eutectoid steel is then cooled very slowly to just above the eutectoid temperature, its structure will remain austenitic. Further cooling to the eutectoid temperature of just below it will cause the entire structure to transform from austenite to a **lamellar structure** of alternate plates of $\alpha$ ferrite and cementite ($\text{Fe}_3\text{C}$). This eutectoid structure is called **pearlite**. See Figure 10.28 and Figure 10.29.

**Figure 10.28** Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.
Example 1:
A 0.76% C eutectoid plain carbon steel is slowly cooled from 750°C to a temperature just slightly below 727°C. Assuming that the austenite is completely transformed to a $\alpha$ ferrite and cementite

(a) Calculate the weight percent eutectoid ferrite formed (Ans: 88.9%)
(b) Calculate the weight percent eutectoid cementite formed (Ans: 11.1%)

Hypoeutectoid steels
(Refer to Figure 10.31 and Figure 10.32)
If a sample of 0.4% C, hypoeutectoid steel is heated to about 900°C (point c) for a sufficient time, its structure will become homogenous austenite. Then if is slowly cooled to temperature at point d, proeutectoid ferrite will nucleate and grow at the austenite grain boundaries.

If this alloy is slowly cooled from temperature at point d to point e, the amount of proeutectoid ferrite formed will continue to increase until about 50% of the austenite is transformed. While the steel is cooling from point d to point e, the carbon content of the remaining austenite will be increased from 0.4% to 0.8%. At 727°C, the remaining austenite will transform isothermally into pearlite according to the eutectoid reaction.

The $\alpha$ ferrite in the pearlite is called eutectoid ferrite to distinguish it from the proeutectoid ferrite.
Figure 10.31  Schematic representations of the microstructures for an iron-carbon alloy of hypo-eutectoid composition $C_0$ (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.

Figure 10.32  Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite. 635×. (Photomicrograph courtesy of Republic Steel Corporation.)
Example 2:
(a) A 0.4% C hypoeutectoid steel is slowly cooled from 940°C to just above 727°C.
   (i) Calculate the weight percent austenite present in the steel (Ans: 51.2%)
   (ii) Calculate the weight percent proeutectoid ferrite present in the steel.
       (Ans: 48.8%)

(b) A 0.4% C hypoeutectoid steel is slowly cooled from 940°C to just below 723°C.
   (i) Calculate the weight percent proeutectoid ferrite present in the steel. (Ans: 51.2%)
   (ii) Calculate the weight percent eutectoid ferrite and weight percent eutectoid cementite present in the steel. (Ans: 43.1%; 5.7%)

Hypereutectoid steels
(Refer to Figure 10.34 and Figure 10.35)
If a sample of 1.2% C hypereutectoid steel is heated to about 950°C (point g), its structure becomes all austenite. Then if this steel is cooled very slowly to temperature at point h, proeutectoid cementite will begin to nucleate and grow at the austenite grain boundaries. With further cooling to just above the eutectic isotherm at 727°C, more proeutectoid cementite will be formed at the austenite grain boundaries and the overall carbon content of the austenite will change from 1.2% to 0.8%. At 727°C, the remaining austenite will transform isothermally into pearlite according to the eutectoid reaction.

The cementite in the pearlite is called eutectoid cementite to distinguish it from the proeutectoid cementite.

Example 3:
A hypereutectoid steel which was slow-cooled from the austenite region to room temperature contains 9.1 wt% eutectoid ferrite. Assuming no change in structure on cooling from just below the eutectoid temperature to room temperature, what is the carbon content of the steel? (Ans: 0.100%)
**Figure 10.34** Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition $C_1$ (containing between 0.76 and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.

**Figure 10.35** Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies. 1000×. (Copyright 1971 by United States Steel Corporation.)
Questions:
1) Distinguish between three types of carbon steels: (a) eutectoid, (b) hypoeutectoid, and (c) hypereutectoid.

2) In a hypoeutectoid steel, both eutectoid and proeutectoid ferrite exist. Explain the difference between them.

3) For a 99.65 wt% Fe–0.35 wt% C alloy at a temperature just below the eutectoid, determine the following:
   (a) The fractions of total ferrite and cementite phases.
   (b) The fractions of the proeutectoid ferrite and pearlite.
   (c) The fraction of eutectoid ferrite.

4) A 0.5% C hypoeutectoid plain-carbon steel is slowly cooled from 950°C to a temperature just slightly above 723°C. Calculate the weight percent austenite and weight percent proeutectoid ferrite in this steel.

5) A 0.5% C hypoeutectoid plain-carbon steel is slowly cooled from 950°C to a temperature just slightly below 723°C.
   (a) Calculate the weight percent proeutectoid ferrite in the steel.
   (b) Calculate the weight percent eutectoid ferrite and weight percent eutectoid cementite in the steel.

6) A 1.05% C hypereutectoid plain-carbon steel is slowly cooled from 900°C to a temperature just slightly above 723°C. Calculate the weight percent proeutectoid cementite and weight percent austenite present in the steel.
7) A 1.05% C hypereutectoid plain-carbon steel is slowly cooled from 950°C to a temperature just slightly below 723°C.

(c) Calculate the weight percent proeutectoid cementite in the steel.

(d) Calculate the weight percent eutectoid cementite and weight percent eutectoid ferrite in the steel.

8) Define the following phases which are present in the Fe-Fe3C phase diagram: (a) austenite, (b) $\alpha$ ferrite, (c) cementite, (d) $\delta$ ferrite
Aluminum Alloys

General Properties of Aluminum
- Aluminum has low density
- Good corrosion resistance in natural environments – oxide film on surface
- Low strength but can be alloyed for better strength
- Nontoxic – used for food containers and packaging
- Good electrical properties
- Relatively cheap

Classification of Wrought Aluminum Alloys
- Classified according to the major alloying elements they contain.
- Four-digit numerical designation
- First number indicates the alloy group which contains specific alloying elements
- The last two digits identify the aluminum impurity
- The second digit indicates modification of the original impurity limits

Wrought Aluminum Alloy Groups

<table>
<thead>
<tr>
<th>Aluminum, 99.00% minimum an greater</th>
<th>1xxx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys grouped by major alloying elements:</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>2xxx</td>
</tr>
<tr>
<td>Manganese</td>
<td>3xxx</td>
</tr>
<tr>
<td>Silicon</td>
<td>4xxx</td>
</tr>
<tr>
<td>Magnesium</td>
<td>5xxx</td>
</tr>
<tr>
<td>Magnesium and silicon</td>
<td>6xxx</td>
</tr>
<tr>
<td>Zinc</td>
<td>7xxx</td>
</tr>
<tr>
<td>Other elements</td>
<td>8xxx</td>
</tr>
<tr>
<td>Unused series</td>
<td>9xxx</td>
</tr>
</tbody>
</table>
- **1000** series are essentially pure aluminum and can be *work hardened*

- **2000** series are alloyed with copper, can be *precipitation hardened* to strengths comparable to steel. Formerly referred to as duralumin, they were once the most common aerospace alloys, but were susceptible to stress corrosion cracking and are increasingly replaced by 7000 series in new designs

- **3000** series are alloyed with manganese, and can be *work-hardened*

- **4000** series are alloyed with silicon. They are also known as silumin.

- **5000** series are alloyed with magnesium, derive most of their strength from *work hardening*. It is suitable for cryogenic applications and low temperature work. However is susceptible to corrosion above 60°C

- **6000** series are alloyed with magnesium and silicon, are easy to machine, and can be *precipitation-hardened*, but not to the high strengths that 2000, and 7000 can reach

- **7000** series are alloyed with zinc, and can be *precipitation hardened* to the highest strengths of any aluminum alloy

- **8000** series is a category mainly used for lithium alloys
**Copper Alloys**

**General Properties of Copper**

- High electrical and thermal conductivity
- Good corrosion resistance
- Ease of fabrication
- Medium tensile strength
- General soldering and joining characteristics
- Controllable annealing properties

**Classification of Copper Alloys**

<table>
<thead>
<tr>
<th>Wrought alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1×××× Coppers and high-copper alloys</td>
</tr>
<tr>
<td>C2×××× Copper-zinc alloys (brasses)</td>
</tr>
<tr>
<td>C3×××× Copper-zinc-lead alloys (leaded brasses)</td>
</tr>
<tr>
<td>C4×××× Copper-zinc-tin alloys (tin brasses)</td>
</tr>
<tr>
<td>C5×××× Copper-tin alloys (bronzes)</td>
</tr>
<tr>
<td>C6×××× Copper-aluminum alloys (aluminum bronzes), copper-silicon alloys (silicon bronzes) and miscellaneous copper-zinc alloys</td>
</tr>
<tr>
<td>C7×××× Copper-nickel and copper-nickel-zinc alloys (nickel silvers)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cast alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>C8×××× Cast coppers, cast high-copper alloys, cast brasses of various types, cast manganese-bronze alloys, and cast copper-zinc-silicon alloys</td>
</tr>
<tr>
<td>C9×××× Cast copper-tin alloys, copper –tin-lead alloys, copper-tin-nickel alloys, copper-aluminum-iron alloys, and copper-nickel-iron and copper-nickel-zinc alloys</td>
</tr>
</tbody>
</table>
Stainless Steels in General
- Excellent corrosion resistance in many environments
- High chromium (Cr) content – at least 12%
- Chromium forms an oxide layer which protects the underlying iron-chromium alloy from corroding
- To produce the protective oxide, the stainless steel must be exposed to oxidizing agents.
- Four main types of stainless steels – ferritic, martensitic, austenitic, and precipitation-hardening

Ferritic Stainless Steels
- Contains about 12% to 30% chromium
- No nickel content
- Relatively low cost
- Highly corrosion resistant
- Magnetic
- Ease of fabrication and joining
- Measures lower strength and toughness
- Cannot be hardened as much as austenitic stainless steels
- New ferritics have very low carbon and nitrogen levels – improved corrosion resistance

Martensitic Stainless Steels
- Contains about 12% to 17% chromium with sufficient carbon (0.15% to 1.0% C)
- Has superior strength and toughness
- Poorer corrosion resistance than ferritic and austenitic types.
- Good machinability
- Magnetic

Austenitic Stainless Steels
- Essentially iron-chromium-nickel alloy
- High formability
- Better corrosion resistance than ferritic and martensitic
- Susceptible to intergranular corrosion
- Non-magnetic
- High hardness
**Cast Irons**
- Cast to desired shapes, not worked in solid state
- Contains 2% to 4% carbon
- Contains 1% to 3% silicon
- Easily melted and very fluid in liquid state
- Superior wear, abrasion, and corrosion resistance
- Low impact resistance and ductility
- Low cost

**Types of Cast Irons**

**Chemical Composition Ranges for Typical Unalloyed Cast Irons**

<table>
<thead>
<tr>
<th>Element</th>
<th>Gray Iron, %</th>
<th>White Iron, %</th>
<th>Malleable Iron, %</th>
<th>Ductile Iron, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>2.5 – 4.0</td>
<td>1.8 – 3.6</td>
<td>2.00 – 2.60</td>
<td>3.0 – 4.0</td>
</tr>
<tr>
<td>Silicon</td>
<td>1.0 – 3.0</td>
<td>0.5 – 1.9</td>
<td>1.10 – 1.60</td>
<td>1.8 – 2.8</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.25 – 1.0</td>
<td>0.25 – 0.80</td>
<td>0.20 – 1.00</td>
<td>0.10 – 1.00</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.02 – 1.0</td>
<td>0.06 – 0.20</td>
<td>0.04 – 0.18</td>
<td>0.03 max</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.05 – 1.0</td>
<td>0.06 – 0.18</td>
<td>0.18 max</td>
<td>0.10 max</td>
</tr>
</tbody>
</table>

**White Cast Iron**
A low-silicon and very brittle cast iron, in which the carbon is in combined form as cementite. A fractured surface appears white.

**Gray Cast Iron**
A cast iron alloyed with silicon in which the graphite exists in the form of flakes. A fractured surface appears gray.

**Ductile Cast Iron**
A cast iron that is alloyed with silicon and a small concentration of magnesium and/or cerium and in which the free graphite exists in nodular form. Sometimes called nodular iron.

**Malleable Cast Iron**
White cast iron that has been heat treated to convert the cementite into graphite clusters; a relatively ductile cast iron.
Figure 13.3  Optical photomicrographs of various cast irons. (a) Gray iron: the dark graphite flakes are embedded in an α-ferrite matrix. 500×. (Courtesy of C. H. Brady, National Bureau of Standards, Washington, DC.) (b) Nodular (ductile) iron: the dark graphite nodules are surrounded by an α-ferrite matrix. 200×. (Courtesy of C. H. Brady and L. C. Smith, National Bureau of Standards, Washington, DC.) (c) White iron: the light cementite regions are surrounded by pearlite, which has the ferrite–cementite layered structure. 400×. (Courtesy of Amcast Industrial Corporation.) (d) Malleable iron: dark graphite rosettes (temper carbon) in an α-ferrite matrix. 150×. (Reprinted with permission of the Iron Castings Society, Des Plaines, IL.)