Skills to Develop

- Outline the general approach for the metallurgy of iron into steel

The early application of iron to the manufacture of tools and weapons was possible because of the wide distribution of iron ores and the ease with which iron compounds in the ores could be reduced by carbon. For a long time, charcoal was the form of carbon used in the reduction process. The production and use of iron became much more widespread about 1620, when coke was introduced as the reducing agent. Coke is a form of carbon formed by heating coal in the absence of air to remove impurities.

The overall reaction for the production of iron in a blast furnace is as follows:

\[
\text{Fe}_2\text{O}_3(s) + 3\text{C}(s) \xrightarrow{\Delta} 2\text{Fe}(l) + 3\text{CO}(g)
\]

The actual reductant is CO, which reduces Fe\(_2\)O\(_3\) to give Fe(l) and CO\(_2\)(g) (Equation \ref{23.2.3}); the CO\(_2\) is then reduced back to CO by reaction with excess carbon. As the ore, lime, and coke drop into the furnace (Figure \ref{fig:23.2.3a}), any silicate minerals in the ore react with the lime to produce a low-melting mixture of calcium silicates called slag, which floats on top of the molten iron. Molten iron is then allowed to run out the bottom of the furnace, leaving the slag behind. Originally, the iron was collected in pools called pigs, which is the origin of the name pig iron.

Figure \ref{fig:23.2.3a}: A Blast Furnace for Reducing Iron Oxides to Iron Metal. (a) The furnace is charged with alternating layers of iron ore (largely Fe\(_2\)O\(_3\)) and a mixture of coke (C) and limestone (CaCO\(_3\)). Blasting hot air into the mixture from the bottom causes it to ignite, producing CO and raising the temperature of the lower part of the blast furnace to about 2000°C. As the CO that is formed initially rises, it reduces Fe\(_2\)O\(_3\) to form CO\(_2\) and elemental iron, which absorbs heat and melts as it falls into the hottest part of the furnace. Decomposition of CaCO\(_3\) at high temperatures produces CaO (lime) and additional CO\(_2\), which reacts with excess coke to form more CO. (b) This blast furnace in Magnitogorsk, Russia, was the largest in the world when it was built in 1931.

The first step in the metallurgy of iron is usually roasting the ore (heating the ore in air) to remove water, decomposing carbonates into oxides, and converting sulfides into oxides. The oxides are then reduced in a blast furnace that is 80–100 feet high and about 25 feet in diameter (Figure \ref{fig:23.2.3b}) in which the roasted ore, coke, and limestone (impure CaCO\(_3\)) are introduced continuously into the top. Molten iron and slag are withdrawn at the bottom. The entire stock in a
furnace may weigh several hundred tons.

Within a blast furnace, different reactions occur in different temperature zones. Carbon monoxide is generated in the hotter bottom regions and rises upward to reduce the iron oxides to pure iron through a series of reactions that take place in the upper regions.

Near the bottom of a furnace are nozzles through which preheated air is blown into the furnace. As soon as the air enters, the coke in the region of the nozzles is oxidized to carbon dioxide with the liberation of a great deal of heat. The hot carbon dioxide passes upward through the overlying layer of white-hot coke, where it is reduced to carbon monoxide:

\[
\ce{CO2}(g) + \ce{C}(s) \rightarrow 2\ce{CO}(g)
\]

The carbon monoxide serves as the reducing agent in the upper regions of the furnace. The individual reactions are indicated in Figure (PageIndex{2}). The iron oxides are reduced in the upper region of the furnace. In the middle region, limestone (calcium carbonate) decomposes, and the resulting calcium oxide combines with silica and silicates in the ore to form slag. The slag is mostly calcium silicate and contains most of the commercially unimportant components of the ore:

\[
\ce{CaO}(s) + \ce{SiO2}(s) \rightarrow \ce{CaSiO3}(l)
\]

Just below the middle of the furnace, the temperature is high enough to melt both the iron and the slag. They collect in layers at the bottom of the furnace; the less dense slag floats on the iron and protects it from oxidation. Several times a day, the slag and molten iron are withdrawn from the furnace. The iron is transferred to casting machines or to a steelmaking plant (Figure (PageIndex{3})).
Steel

Much of the iron produced is refined and converted into steel. Steel is made from iron by removing impurities and adding substances such as manganese, chromium, nickel, tungsten, molybdenum, and vanadium to produce alloys with properties that make the material suitable for specific uses. Most steels also contain small but definite percentages of carbon (0.04%–2.5%). However, a large part of the carbon contained in iron must be removed in the manufacture of steel; otherwise, the excess carbon would make the iron brittle. However, there is not just one substance called steel - they are a family of alloys of iron with carbon or various metals.

Impurities in the iron from the Blast Furnace include carbon, sulfur, phosphorus and silicon, which have to be removed.

- **Removal of sulfur:** Sulfur has to be removed first in a separate process. Magnesium powder is blown through the molten iron and the sulfur reacts with it to form magnesium sulfide. This forms a slag on top of the iron and can be removed. $\text{Mg} + \text{S} \rightarrow \text{MgS}$
- **Removal of carbon:** The still impure molten iron is mixed with scrap iron (from recycling) and oxygen is blown on to the mixture. The oxygen reacts with the remaining impurities to form various oxides. The carbon forms carbon monoxide. Since this is a gas it removes itself from the iron! This carbon monoxide can be cleaned and used as a fuel gas.
- **Removal of other elements:** Elements like phosphorus and silicon react with the oxygen to form acidic oxides. These are removed using quicklime (calcium oxide) which is added to the furnace during the oxygen blow. They react to form compounds such as calcium silicate or calcium phosphate which form a slag on top of the iron.

<table>
<thead>
<tr>
<th>Table: Special Steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>iron mixed with</td>
</tr>
</tbody>
</table>

Figure: Molten iron is shown being cast as steel. (credit: Clint Budd)
Cast iron has already been mentioned above. This section deals with the types of iron and steel which are produced as a result of the steel-making process.

- **Wrought iron**: If all the carbon is removed from the iron to give high purity iron, it is known as wrought iron. Wrought iron is quite soft and easily worked and has little structural strength. It was once used to make decorative gates and railings, but these days mild steel is normally used instead.

- **Mild steel**: Mild steel is iron containing up to about 0.25% of carbon. The presence of the carbon makes the steel stronger and harder than pure iron. The higher the percentage of carbon, the harder the steel becomes. Mild steel is used for lots of things - nails, wire, car bodies, ship building, girders and bridges amongst others.

- **High carbon steel**: High carbon steel contains up to about 1.5% of carbon. The presence of the extra carbon makes it very hard, but it also makes it more brittle. High carbon steel is used for cutting tools and masonry nails (nails designed to be driven into concrete blocks or brickwork without bending). High carbon steel tends to fracture rather than bend if mistreated.

- **Special steels**: These are iron alloyed with other metals (Table 1).

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<table>
<thead>
<tr>
<th>stainless steel</th>
<th>chromium and nickel</th>
<th>resists corrosion</th>
<th>cutlery, cooking utensils, kitchen sinks, industrial equipment for food and drink processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>titanium steel</td>
<td>titanium</td>
<td>withstands high temperatures</td>
<td>gas turbines, spacecraft</td>
</tr>
<tr>
<td>manganese steel</td>
<td>manganese</td>
<td>very hard</td>
<td>rock-breaking machinery, some railway track (e.g. points), military helmets</td>
</tr>
</tbody>
</table>

*Video: You can watch an animation of steelmaking that walks you through the process ([https://www.youtube.com/watch?v=ngzJk2836V6](https://www.youtube.com/watch?v=ngzJk2836V6)).*
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- Jim Clark (Chemguide.co.uk)