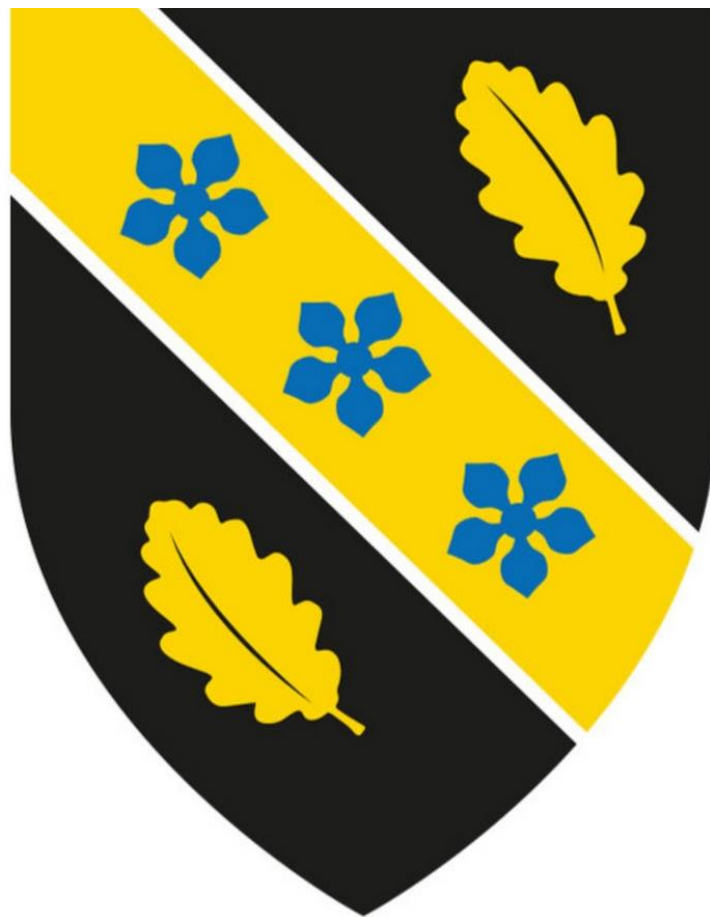


University of Wales Trinity Saint David
School of Engineering

Steel production and the Future of Steel
Physical Science for Materials ACMA4001



Julian Edwards
2315607

Contents

1	Production of Pig Iron and Basic Carbon Steels	i
1.1	Producing Pig Iron.....	i
1.2	Producing Basic Carbon Steel	ii
2	Mechanical Properties.....	iii
3	Electrical and Thermal Conductivity Properties	iv
4	Material Selection Table.....	v
5	The Future of Steel.....	vi
6	Bibliography	vii

1 Production of Pig Iron and Basic Carbon Steels

1.1 Producing Pig Iron

There are many critical steps when creating carbon steels. One of which is the production of pig iron inside of a blast furnace (see Figure 1.1), which aims to remove the oxide layer as well as most other impurities from the iron ore.

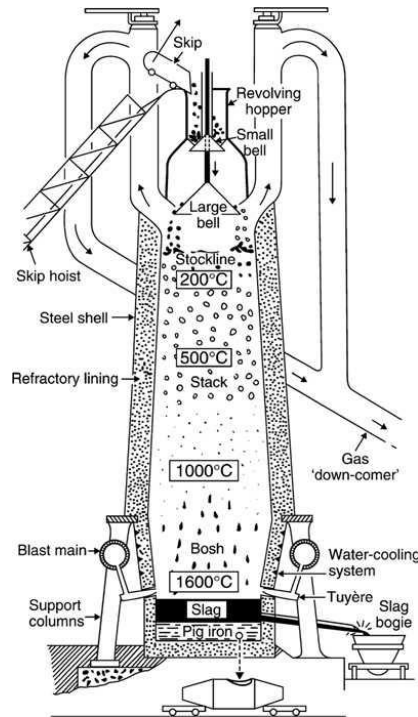
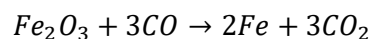


Figure 1.1 - Modern Blast Furnace (Bolton, 2020)

The process begins by gathering the processed ore, coke, and limestone which are then fed into the top of the blast furnace which is then heated to high temperatures. ‘Air that has been preheated to temperature from 900°C to 1250°C’ (Britannica, 2024) is then pushed into the blast furnace with an appropriate fuel ‘through the tuyères’ (Bolton, 2020) which are the nozzles located near the bottom of the furnace. The hot air is then able to react with the coke which creates a large amount of carbon monoxide (CO) gas which will act as the ‘reducing gas’ (Britannica, 2024) which will continue to rise throughout the furnace. The carbon monoxide combined with the high temperatures (up to 1600°C (Bolton, 2020)) will start to perform reduction on the iron ore, the primary reaction can be seen in the below chemical equation (adapted from (Bolton, 2020)):



This equation demonstrates the carbon monoxide reacting with the oxygen present in the iron ore and reacting to create carbon dioxide (CO₂) so only Iron or “pig iron” remains. There are also several other minor reactions to help reduce the impurity in the iron, this is achieved by having the impurities reacting with another chemical, such as limestone. There are several side products and waste created

by this reaction '(mainly silica, SiO_2)' (Bolton, 2020) which will then combine to create slag which can then be reprocessed into other products such as cement. Once completed, the molten iron produced can then be used for steel making or can be cast into 'pigs' for use in an iron foundry as stated by (Bolton, 2020).

1.2 Producing Basic Carbon Steel

After the blasting process has been completed, the pig iron is ready to be reprocessed in a basic oxygen furnace (see Figure 1.2). This process (also known as Basic Oxygen Process (BOP) or Basic Oxygen Steelmaking (BOS)), primarily, has a similar purpose to pig iron production, which is 'the oxidation of impurities present' (Bolton, 2020).

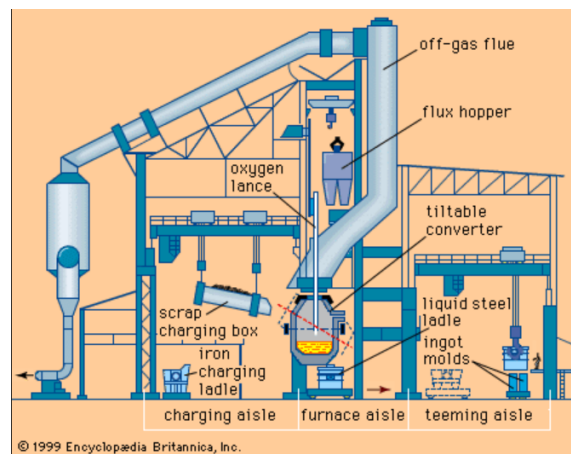


Figure 1.2 – Basic Oxygen Furnace (Britannica, no date)

The first stage in the BOS process is to load scrap metal and 'lime and other fluxes' (Britannica, no date) into the oxygen furnace followed by the molten pig iron from the blast furnace which will help to melt and break down the scrap to be recycled due to the high temperature. The oxygen lance can then be lowered into the oxygen furnace and 'oxygen is injected into the bath as supersonic velocities' (Britannica, no date). The injected oxygen is of a high purity meaning there is little nitrogen and other elements that could react with the iron which could influence the mechanical properties. The high purity of oxygen 'initiates a series of intensively exothermic' (Britannica, no date) reactions including impurities being oxidised creating another layer of slag. Several reactions can occur simultaneously, including the oxidation and loss of some iron in the process. Once the oxygen injection has finished, the slag that was created is then 'run off and any adjustments made to the carbon content of the charge' (Bolton, 2020). The impurities (intentional or unintentional) will determine the steel's mechanical properties. Additionally, several elements could be added to change the properties of the steel such as chromium and nickel to make stainless steel which resists corrosion, or by adding manganese to make manganese steel which can be very tough.

2 Mechanical Properties

Steel is primarily an alloy of Iron and Carbon, and together they can be significantly stronger than regular iron and have improved mechanical properties. Increasing the carbon content of steel can increase the overall hardness, yield point, and tensile strength (Dalton, 2020), however, carbon can negatively impact some properties if it is not used in moderation. For example, when hardness increases in a material, so does the brittleness, it can also decrease the corrosion resistance of the steel making it less suitable for open environments. Most elements will have both negative and positive impacts on steel, such as manganese which increases the toughness but generally has a lower tensile strength when compared to carbon steel. While there may be materials that offer more / better mechanical properties than carbon, mechanical properties are the only factors that are considered when producing steel.

There are several reasons why carbon is used as opposed to other elements:

Firstly, carbon is cost-effective and is abundantly available in a wide range of sources especially compared to other elements which can be very rare or expensive.

Another reason is that it is easy to control, manufacturers can easily control the carbon content of a steel product accurately to get their desired mechanical properties. If too much carbon content was added to the steel, it would be possible to remove or dilute it by reprocessing in the basic oxygen furnace meanwhile other elements may be harder to separate due to their bonds.

Carbon is also easy to work with compared to other elements, carbon can be directly dissolved into FCC (face-centred cubic, see Figure 2.1) iron for 'up to a maximum of 2.0%' (Bolton, 2020) carbon content, this allows the carbon to form bonds in between the iron lattice, so it can benefit from the strength of the between carbon atoms as well as the bonds of the iron atoms. Together these bonds can greatly increase the strength and toughness of the alloy.

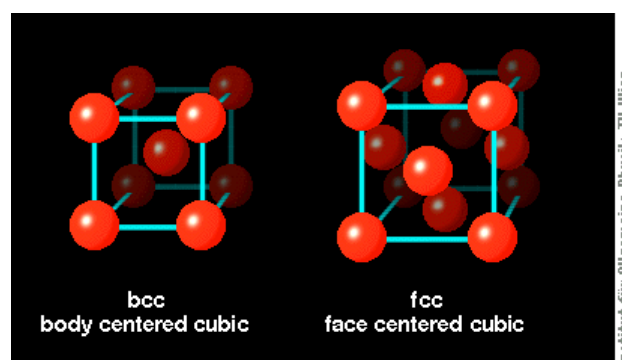


Figure 3.1 - BCC and FCC Structures (TU Wien, no date)

The atomic structure of carbon is useful for alloying with iron due to its relatively small size as well as its solubility in FCC iron which enables it to form a solid solution inside of the iron lattice.

3 Electrical and Thermal Conductivity Properties

In general, ferrous metals or iron-based alloys have a relatively low electrical conductivity compared to non-ferrous (e.g. Copper) metals but are higher when compared to semi-conductors, this is due to impurities within the materials. As for thermal conductivity, ferrous metals have a medium to high thermal conductivity. Due to the properties of ferrous metals, they do not have suitable electrical conductivity applications, but they have some thermal conductivity applications such as piping systems or boilers.

Non-ferrous metals are very good at conduction due to them having more free electrons allowing for better electrical conduction than ferrous metals semi-conductors. They are also generally better at thermal conductivity due to the extra mobility of electrons as well and their atomic structures are usually FCC which helps to provide pathways for thermal energy. Its properties allow for many uses both electrical and thermal such as electrical wiring or heat sinks.

Semi-conductors typically offer electrical conductivity between metals and insulators, this is due to the band gaps in the material making it significantly more difficult for electrons to travel. The electrical conductivity can easily be altered by the process of doping which can either help bridge the gap between band gaps or block the path. As for their thermal properties, they are generally poor to medium thermal conductors. These properties make them ideal for use in electronic components inside electrical devices.

Insulators offer both very poor electrical conductivity and low thermal conductivity, this is due to the very large band gap and have very few free-moving electrons to assist in electron movement. This makes them useful for insulating wiring to prevent electrical failure or insulating houses to reduce heat transfer.

4 Material Selection Table

Table 4.1 – Material Selection Table (Modified from source: (Ashby, 2016), (Bolton, 2020))

Property	Low Carbon Steel	Medium Carbon Steel	High Carbon Steel
Carbon %	0.15 - 0.25	0.25 - 0.60	0.60 - 1.50
Density (kg/m ³)	7800 - 7900	7800 - 7900	7800 - 7900
Young's Modulus (GPa)	200 - 220	200 - 220	200 - 220
Yield Strength (MPa)	250 - 400	310 - 900	400 - 1200
Ultimate Tensile Strength (MPa)	350 - 580	410 - 1200	550 - 1600
Specific Heat Capacity (J/kg*K)	460 - 510	440 - 520	440 - 510
Thermal Conductivity (W/m/K)	49 - 54	45 - 55	47 - 53
Resistivity ($\mu\Omega\cdot\text{cm}$)	15 - 20	15 - 22	17 - 20

Table 4.1 (above) contains a sample of mechanical and physical properties of three plain carbon steels, which have been generalised as 'Low', 'Medium', or 'High' carbon steels each with a different carbon content. As can be seen above, the carbon content has little to no effect on most mechanical and physical properties but has a large effect on the Yield Strength and Ultimate Tensile Strength making the steels with a larger carbon content much stronger in comparison.

5 The Future of Steel

Steel is an extremely useful material due to its mechanical properties and the ability to change those properties to match its needs almost perfectly. Not only can the properties be changed by adding another element, but it is also cost-effective especially when strength, durability, and recyclability are taken into consideration.

Steel already has many applications in almost all sectors around the world and has become one of the key materials in modern-day infrastructure. Some examples of this include modern machinery used in factories around the globe, bridges that connect towns and cities, as well as in many large buildings as supports which are used daily. Its versatility allows it to become almost any shape, size, and strength, research and development are carried out every day on steel making advancements in steel grades and increasing their versatility. One of the largest concerns of steel production is the extremely large carbon footprint it leaves on the environment, but even that is being reduced by advancements in technology such as the Electric Arc Furnace which is being adopted by companies worldwide.

Have we exhausted all the potential of steel? It is very unlikely. Every step of the steelmaking process is being scrutinised to improve efficiency as well as improve the mechanical and physical properties. The possibilities of steel, while not endless, are vast, the limit is primarily our knowledge and technology as well as our current needs. There is ongoing research that is making many interesting possibilities for steel in the future such as the use of shape-memory alloys which could show adaptive properties, or steel composites, like combining steels with polymers for better performance.

There are many mysteries to steel that we have yet to discover, there may be combinations of elements that may have a positive effect on mechanical properties, or there is technology that will allow us to further control the mechanical properties. Even if the applications of steel have been exhausted, it is still a key material used in many structures around the world and plays a key role in modern infrastructure.

Overall, Steel is a very useful material that is strong, durable, versatile, and cost-effective. While there are currently hundreds if not thousands of steel applications, there are still many possible secrets that can be unlocked, and its potential has yet to be exhausted. It will continue to be a critical material in every area of engineering, architecture, and technology, and when it has run its course, it can be recycled to produce new steels or even new materials.

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