1

History of steelmaking

1.1 How it all began

Early smelting of metals began with the Arabic science from about 3500 BCE (before the Common Era) in Egypt and the Near East (Sumer), with smelting of copper, gold, mercury and alloys like bronze [1]. Initially, pure iron from meteorites was used for decoration and making spearheads. Learning to smelt iron (Fe) from its ore oxide (Fe_2O_3) became commonplace in Egypt only around 2000 BCE, and it began to replace bronze in Europe c. 1000 BCE. Iron's high melting point at 1535 °C for pure iron, in contrast to copper at 1083 °C, required smelting furnace construction to develop rapidly to reach such high temperatures. Iron ore, being the second most abundant metal in the earth's crust [2] after aluminium, heralded the commencement of the so-called Iron Age in the British Isles from about 800 BCE until the Roman invasion of 43 CE (Common Era).

Iron ore can be found in four mineral sources:

- Magnetite at 65% iron; not available in Britain [3];
- Haematite at 50% iron concentration, present as separate, blue-tinged so-called kidney iron [3];
- Blackband at ~30% concentration found in coal seams [4]; and
- Jurassic iron at only ~20% concentration discovered across England from the North Yorkshire Moors to the Cotswold Hills in the south–west [4].

Early ironmaking processes involved bloomeries, where partially enclosed fires built on exposed positions provided a sufficient blast of natural wind for the required draught [1]. The term 'bloomeries' was coined due to the putty-like mass of hot iron that was extracted from the furnace and then forged with hammer and anvil into a bloom. The output was limited to only a few kilograms of iron blooms per day, which were used to make tools and small bladed weapons. The molten iron at 4% carbon would run off into shapes moulded in the sand that resembled a sow with her sucklings, which gave rise to the term 'pig-iron', now called cast iron. The first use of cast iron in building and construction dates back to 1380 CE in Europe. This cast iron was only made in very small quantities, which were reheated – to obtain reduced surface carbon. This produced the so-called wrought or bar iron, which was malleable

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enough to be worked after [1]. In the United Kingdom, in the 1700s, indigenous iron production accounted for only 12,000 tonnes/p.a. Eventually, to overcome the challenges of difficult supply routes for timber and coal needed in the then-still inefficient furnaces, multiple small ironmasters organised themselves and banded together in small iron-producing areas, such as South Wales. Additionally, the industry required a high labour force, which resulted in very high costs. As a direct result of these costs, most iron was therefore being imported into the United Kingdom, particularly in quantities of cheaper imports from Sweden. Back then, ca. 50% of the iron used in Britain came from Sweden [1].

1.2 First attempts at steelmaking

Steel is defined to be as a commercial *iron* (hard metal; oxidises easily when exposed to air) [5] that contains *carbon* (chemical element; key ingredient for most life on earth; forms pliable *graphite* [crystalline carbon] and also diamonds – one of the hardest materials in the world; the basis for graphene) in amounts of up to about 1.7% as an essential *alloying* constituent (a substance composed of two or more metals or of a metal/non-metal combination intricately united commonly by being fused together and dissolving in each other when molten) [6], which is malleable when exposed to suitable conditions and is distinguished from *cast iron* (molten iron filled into moulds) by its malleability and lower carbon content. The first evidence of steelmaking is from the thirteenth century and has been discovered in medieval Anatolia, Kubadabad (Türkiye) [7]. A timeline of the steelmaking process evolution is shown in Figure 1.1.

1.3 Steelmaking process development

Although evidence of early efforts in steelmaking was discovered in the thirteenth century CE [7] in the Arab world, it is argued that actually the earliest known use of the crucible steel production technique occurred in India and central Asia in the early first millennium CE [8–13].

Documented early attempts to refine the process do not seem to have had a great impact on the craft, until the nineteenth century CE. In c. *1865* [8–10], Robert F. Mushet discovered that by adding *manganese* (manganese oxide crystals consist of MnO 6 octahedral units shared by corners and/or edges) to Bessemer steel [14], casting (filling the void of a mould with molten steel) of ingots (an oblong piece of metal) free of blowholes was possible, and adding manganese also reduced the metal brittleness forced by the presence of *sulphur* (yellow crystal, often with pungent smell) [15]. Mushet [8–10, 13] produced the first commercial alloy steel in 1868 when he found that adding *tungsten* (also: Wolfram) to steel [16], particularly *after* air cooling, significantly increased its hardness, which lead to this material further on forming the basis of the subsequent development of tool steels for the machining of metals [17].

- 1990 64% of total steel produced is continuously cast
- 1989 World steel production 770 million tons
- 1960–80 Development of micro-alloyed steels
- 1970s Mini-mills and electric arc furnaces
- 1970 5% of total steel produced is continuously cast
- 1965 2% of total steel produced is continuously cast
- 1962 Micro-alloyed steel; 0.01–0.05% niobium/vanadium
- 1960 OBM oxygen-bodenblasen-Maxhuette
- 1955–65 Degassing systems, Germany;
- 1950 50 tons/20 megavolt-amperes
- 1950 UK: United Steel Co., Development continuous casting
- 1949 Austria: Linz-Donawith (LD) process
- 1933 Perrin process, removing sulphur
- 1920 Furnace size increased to 30 tons capacity; electricity
- 1918 US; adding molybdenum reduced brittleness
- 1914 UK; Brearly; stainless steel, 0.4% carbon/13% chromium
- 1912 Germany, addition of nickel to stainless steel patented
- 1911 Germany; Philip Monnarts: 8% chromium dissolved in iron matrix
- 1907 Switzerland; electric melting in acid-lined furnaces
- 1904 US; first rolling mills
- 1899 Paul Heroult; electric arc furnaces melting 1 ton steel replaced crucible steel making
- 1895 Germany, Hans Goldschmidt developed low-carbon ferro-chromium
- 1893 Tropenas converter was invented
- 1882 UK; Hadfield makes steel containing 12–14% manganese/1% carbon
- 1878 Gilchrist & Thomas invented the basic-lined converter
- 1877 Ferranti induction furnace
- 1872 UK; Woods & Clarke developed alloy containing 30–35% chromium
- 1871 Germany; Siemens invented the regenerative gas furnace
- 1868 UK; Mushet adding tungsten to steel increased hardness
- 1861 UK; first press forge built
- 1860 Germany/Franee; Siemens & Martin developed the open hearth
- 1856 UK; Bessemer invented the first converter
- 1820 UK; first alloy steel, Stodard & Farraday added gold & silver to improve corrosion resistance
- 1798 chromium identified as chemical element; extracted as iron-chromium-carbon-alloy
- 1766 UK; John Prunell grooved rolls for producing rods from puddled iron
- 1740 UK; Benjamin Huntsman refined the crucible process
- Thirteenth century first evidence of steelmaking in Medieval Anatolia, Kubadabad
- 800 CE metal manufacturing methods established in Northern Europe
- First century CE metal component production established across India and Central Asia
- 2000 BCE smelting iron ore from iron oxide in Egypt and the Near East
- 4000 BCE smelting of copper, gold, mercury and alloys like bronze

Figure 1.1 A timeline of steelmaking process evolution [8–13].

In 1882, the inventor Robert Hadfield [8–10, 13] developed a steel containing up to 14% manganese and 1% carbon that greatly improved wear resistance, which was subsequently used in jaw-crushers and railway crossover points.

In 1889, however [8–10, 13], the real driving force for alloy steel development was discovered: armaments. This discovery caused the production of steel containing only 0.3% carbon and 4% nickel, which was subsequently improved further by adding *chromium* [18]. In 1918, steel was made less brittle by adding *molybdenum* [19].

1.3.1 Micro-alloyed steels

An important development that occurred immediately after the Second World War was the improvement in steel compositions for sections that could readily be welded by increasing the manganese content to 1.5% and maintaining the carbon content below 0.25% [17]. *By 1962*, high-strength low-alloy (HSLA) steel, and subsequently the term 'micro-alloyed steel', was introduced for mild-steel compositions, which contained 0.01–0.05% *niobium* [20] and similarly *vanadium* [21] (used for making ferrovanadium or as an additive to steel) [22]. In the period 1960–1980, the development of micro-alloyed steels evolved rapidly by exerting control over the environmental temperature during rolling, where yield strengths could be increased by almost 200%, in comparison with conventional mild steel [23].

1.3.2 Stainless steels

Chromium was first used by Stodart and Faraday in *1820* and John Woods and John Clark in *1872* to produce an alloy containing up to 35% chromium [8, 13]. *In 1895*, commercial success became possible when Hans Goldschmidt in Germany [12] invented the method of producing low-carbon *ferrochromium*. Eventually, in *1911*, Philip Monnartz in Germany established the relationship between the carbon content of chromium steels and their corrosion resistance [12, 13], but through the ensuing interwar period, it became standard practice to add at least 8% chromium dissolved in the iron matrix. Exposure to air caused the formation of a protective layer of chromic oxide to build up on the steel surface. Around *1914* [12, 13], more corrosion-resistant steel was being produced by adding 0.4% carbon and 13% chromium, developed by Harry Brearley in Sheffield, United Kingdom, with the purpose of producing cutlery in mind. Although Brearley's steel trials in *1914* [24] showed that 3.5% of the chromium was connected with the carbon, there was still sufficient remaining chromium to establish corrosion resistance. In Germany in *1912* [25], adding nickel to stainless steel was patented by Thyssen-Krupp, but the compositions had not been commercially exploited before *1929*, when 18/8 austenitic steel (18% chromium, 8% nickel and 0.2% carbon) was started to be produced on a larger scale, mainly exploited by the chemical industry. By the late *1930s*, austenitic stainless steels and modified compositions were mainly used by the military, when the early jet aircraft engines were produced during the second World War [12], which are still being used and produced using these parameters today. In the *1950s*, the production of steel with high strength and corrosion/wear resistance was mainly driven by the demands of the chemical industry. It brought the development of Duplex stainless-steel forward: alloys with a microstructure consisting of 65% ferrite/austenite, 25% chromium, 5% nickel, 3% *copper* and 2% molybdenum [4].

1.3.3 Tubes

Since *1824* [8–13], when pressure butt welding of heated, curved metal strips was invented in Britain, similar processes are still commonly used today for producing seamed tubing. However, in c. *1921*, this process was immensely improved in the United States, when the seam was joined by electric resistance welding instead of pressure butt welding [9, 10]. To this day, seamed tubes are still being manufactured using this method, whereby particularly large-diameter tubes are being formed by spirally coiling a continuous strip of steel around, which then arc-welds the spiral seam.

1.3.4 Seamless tubing

Seamless tubing is a hollow cylinder of metal (often steel, stainless steel, titanium, or other alloys) made by extrusion or piercing a solid billet, without any joints or welds. This results in a smooth, continuous structure throughout the tube length. The requirement for seamless tubing meant the requirement for piercing of a round billet, which was developed in Britain in 1841 [12]. Since *1886*, when the Mannesmann company in Germany under Reinhard and Max Mannesmann [26] developed the process of rolling the billet longitudinally and at the same time forcing it onto a piercing bar called a mandrel [12], ferrous/non-ferrous metals are formed.

1.3.5 Plates and sheets

Plates are produced by hot rolling [8, 21, 25], and in order to produce steel sheets from crude plates, the steel needs to be cold-rolled in mills. These mills consist of different stands in sequence, fitted with an initial big and then decreasing-sized double rolls, where crude steel plates pass through the rolling stands sections. The first mill of this type was installed in *1904* in the United States [13].

1.3.6 Timeline of steel production processes

With the earliest known use of the *crucible* steel production technique occurring in India and Central Asia in the early first millennium CE [8–13], archaeological investigations have provided us with the evidence that these techniques applied were quite crude but efficient: wrought iron was heated in closed oven-like furnaces, together with charcoal and materials rich in carbon, and the end-product of this process was known as wootz or Damascus steel. It is thought that trading activity with Middle Eastern countries resulted in obtaining the knowledge about these techniques to reach the Northern Hemisphere, as records indicate that the crucible process was applied in 800 CE in Northern Europe – amongst other evidence, these were utilised to produce the Ulfberht Viking swords [27].

Staying for a moment with the Northern Hemisphere, it has been established that the person deserving the title of founder father of British steelmaking was the inventor and engineer Henry Bessemer [8, 13, 28], whose work was later referred to as the driving force to initiate a process by which a superior issue of cast iron for the manufacture of guns was invented in 1856 [12, 29]. Bessemer conducted a series of experiments and decided to carry out a trial using a converter: bringing air into contact with a specific amount of molten crude iron with the aim of converting it into malleable iron [8, 12, 13, 28, 29]. The first converter was built at Baxter House, St. Pancras, London, which featured a brick-lined cylindrical body, and the base was furnished with holes through which air could be blown.

At the first trial, after 7 cwt (cwt = hundredweight, which equals a hundred metric pounds) [30] of molten pig iron was poured in, ambient air at 10–15 lb. pressure was blown through the bottom holes, and after approximately 10 minutes, a violent reaction ensued, by which the oxygen in the air and the carbon in the pig iron were started sending up an exponentially increasing eruption of sparks and formed a voluminous white flame. A series of minor explosions threw molten slags and splashes of metal high up in the air – rendering the converter a veritable volcano in a state of active eruption [8, 12, 13, 28, 29]. After another 10 minutes, the violent reaction and the flame had died down, indicating the process was complete. The contents of the converter were poured into a shallow pan or ladle, forming the metal into an ingot, and upon testing, it was found to be wholly decarbonised, malleable iron – heralding the era of modern steel production [13].

As exciting as this breakthrough was, there was one apparent difficulty with Bessemer's process [13]: it could only convert pig iron low in phosphorus and sulphur into the desired malleable steel. Whilst these would have been quite easy to remove by adding a basic flux, such as lime [31], the resulting basic slag would have degraded the acidic refractory lining (bricks). However, there were good supplies of iron ores low in phosphorus in Britain and the United States [2, 3, 6], but they were far more expensive.

In *1878*, the engineers and inventors Sidney Gilchrist Thomas and Percy Gilchrist built a basic-lined converter, using calcined dolomite as the refractory material [8, 12]. This approach made it possible to use a lime-rich slag, which held phosphorus and sulphur in solution. At odds with its potential, this 'basic Bessemer' process [12] was surprisingly little used in Britain or the United States, which gave the industries of Alsace and Lorraine a competitive advantage, as they were able to use the prevalent phosphoric ores [13, 32]. This catapulted the development of the Belgian, French and German steel industries to the top position in world production of steel, which rose to about 50 million tonnes by 1900 [2, 3, 6, 13, 32].

In 1995, Webb reviewed [29] the work of German author Wengenroth, who investigated the coexisting British and German steel manufacturing industries between 1865 and 1995. At the very beginning of the steel production era, British steel was the dominating force worldwide [2, 3, 6, 13, 32]. However, German ingenuity won the better over the British steel industry eventually and developed mechanisms and processes that would lay the technological foundations for German expertise and dominance over the British steel industry over the next century [29].

Carr and Taplin [8], as well as Webb [29], also researched the processes involved in steel production and identified the following key elements:

1) Puddling: wrought iron production, converting pig iron (cast iron) into wrought by applying heat, stirring frequently in a furnace in the presence of oxidising substances [33]. Wrought iron is produced by heating iron and repeatedly hammering and shaping it using specialised tools.
2) Crucible steel processes [34] for producing fine or tool steel. Crucible steel is a high-quality steel made by melting iron and carbon in a crucible (a ceramic or metal) container.

In *1740*, Benjamin Huntsman decided to refine the process by heating small pieces of carbon steel in a closed fireclay case, which was covered in *coke* (pyrolysis process: heating coking coal to c. 1000–1100 °C in the absence of oxygen to drive off volatile compounds [17]) and set alight. When the temperature rose to 1600 °C/2900 °F, the steel started melting for the first time and produced a homogeneous metal of uniform composition, which was then used for manufacturing watch and clock springs [17].

In order to improve specific properties such as strength, wear and corrosion resistance, alloying elements were added to steels.

In *1820,* the first experimental study of alloy additions to steel was made by the Britons James Stodart and Michael Faraday, who added gold and silver to steel in an attempt to improve its corrosion resistance. The mixtures were not commercially feasible, but they initiated the idea of adding chromium to steel (see Stainless Steel) [17].

In the *1860*s, William and Friedrich Siemens in Britain and Pierre and Émile Martin in France developed the 'open hearth' steelmaking process. Combustion gases preheated air and fuel gas to 800 °C (1450 °F), whereby a flame temperature of about 2000 °C (3600 °F) could be obtained enough to melt the inserted charge. Refining was achieved by causing a reaction between the slag (to which iron ore was added) and the liquid metal in the hearth of the furnace, inducing the removal of carbon, manganese and silicon [35] from the metal, and furnace capacity gradually increased to 100 tonnes and eventually to 300 tonnes. Acid-lined furnaces were used at first, but later a basic process was developed, which facilitated the removal of phosphorus and sulphur from the charge. Sufficient heat could be produced in 12–18 hours, providing an adequate time frame for analysis of the material and adjusting its composition before it was tapped from the furnace [17]. Although Britain had better access to ore and pig iron, from sites across Britain, production was first acidic and then basic, and finally it used open-hearth Siemens–Martin furnaces that made steel cheap enough for mass production during the last third of the century [36].

After *1870,* the coke-fire furnace was replaced by the Siemens regenerative gas furnace [17], as it produced even higher temperatures than the open-hearth furnace. The Siemens furnace was furnished with a series of combustion holes, with each hole holding several *crucibles* (a vessel that does not melt easily and is capable of withstanding high temperatures; Definitions.net, 2020), and was capable of heating as many as 100 crucibles at a time. In the twentieth century, the electric furnace replaced the crucible process, which was used to produce high-quality tool steel and high-speed steel in countries where electric power was cheap [17].

Parallel to the already mentioned developments and with the increased levels of efficacy of the electric power industry towards the *end of the nineteenth century*, the use of electricity as an energy source in steelmaking became increasingly important. *Around the 1900s*, small electric-arc furnaces with a melting capacity of c. 1 tonne of steel, replacing crucible steelmaking, were in use to primarily make tool steels [17], and by 1920, furnace size had increased to a production capacity of 30 tonnes. This was achieved by furnishing electricity supply with a three-phase 7.5 megavolt-amperes, where three graphite electrodes were being fed through the roof of the furnace and the arcs forming between the electrodes and the charge in the hearth.

In *1933,* the expensive Perrin process for removing sulphur was developed, where steel was poured into a ladle containing a liquid-reducing slag; violent mixing occurred by which sulphur was transferred from the metal mass to the slag.

In the post-war period, desulphurising powders based on calcium, silicon and magnesium were injected into the liquid steel in the ladle through a lance using an inert carrier gas, which was the method first developed in Japan to initially produce steels for gas and oil pipelines [17].

In *1949*, the Linz–Donawitz (LD) process was developed in Austria [29, 37]. Using a new approach, oxygen was blown through a lance into the top of a pear-shaped vessel, whose outer shape very much resembled the Bessemer converter [17]. As there was no inert *nitrogen* gas (inert/diatomic gas: colourless, odourless and tasteless) present in the air, which would have provided a cooling effect, any heat not lost to the off-gas was being used to melt scrap added to the pig iron charge. A basic slag was then produced by adding lime to the charge, thus removing phosphorus and sulphur, establishing the known basic oxygen process (BOP). With BOP, it became a reality to produce 200 tonnes of steel from a charge consisting of up to 35% scrap in a tap-to-tap time of 60 minutes. The charges in BOP-applying furnaces were increased to 400 tonnes, and, provided low-silicon charges were being used, blowing times were reduced to less than 20 minutes [17]. In quick succession of the LD process, an improved method was developed where burnt lime along with oxygen was blown through the lance [17], later known as the LD-AC (after the ARBED steel company of Luxembourg & Centre National of Belgium) or the oxygen–lime powder (OLP) process, which led to a more effective refining of pig iron smelted from high-phosphorus European ores [17].

After the Second World War, the increasing need for improved properties of steel was a driver for the development of continuing the refining in the ladle *after* steel had been tapped from the furnace, as opposed to stirring the liquid in the ladle through means of blowing a jet of argon through the mass. Reduced variations in the temperature and composition of the metal caused solid oxide inclusions to rise to the surface and become absorbed by the slag, as well as dissolved gases such as hydrogen, oxygen and nitrogen. However, when casting large ingots, gas stirring alone could not remove hydrogen to an acceptable level. *After 1950,* and as large vacuum pumps were commercially available, ladles were placed in large, evacuated chambers, where hydrogen to less than two parts per million was removed by blowing argon as a matter of stirring the mass. In Germany between *1955 and 1965,* a variety of improved degassing systems of this type were developed, which later proved to be of great benefit to the steelmaking industry [17].

Around 1950, furnace capacity had increased to 50 tonnes and electric power to 20 megavolt-amperes [17]. As little to no refining occurred, small arc furnaces, which were lined with acidic refractories, were considered little more than melting units, whereas larger furnaces were basic-lined, and a lime-rich slag was produced by which silicon, sulphur and phosphorus were being removed from the melt. These were so efficient that they could be operated with a charge that was entirely scrap or a mixture of scrap and pig iron, and steel of excellent quality with sulphur and phosphorus contents of as low as 0.01% could be produced. *By 1950*, this electric arc process, being ideally suited for producing low-alloy steels, had almost completely replaced the basic open-hearth process in this capacity. During this time, electric arc furnaces produced c. 10% of all the steel of c. 200 million tonnes manufactured worldwide and basic electric arc furnaces accounted for almost 30% of steel production by 1989, when the world steel production accumulated to 770 million tonnes of steel [17].

In the *mid-1960s,* two concentric *tuyeres* (a nozzle/lancet through which air is pressed into a furnace, forge or smelter) [38] with a hydrocarbon gas in the outer annulus and oxygen in the centre were used in Germany and Canada, effectively constituting a return to the original bottom-blown Bessemer concept: the OBM process (for ***o**xygen **b**odenblasen **m**axhuette*, 'oxygen bottom-blowing Maxhuette'), which was in North America called Q-BOP (quick basic oxygen process; a Q-BOP furnace has no overhead lance, and the oxygen is blown in through tuyeres (pipes) at the bottom of the furnace). Eventually, all oxygen steelmaking processes replaced the open-hearth and Bessemer processes on both sides of the Atlantic [17].

1.4 Casting

Steel-forming operations were on a relatively small scale until the introduction of the Bessemer process, in which large volumes of liquid steel were produced for the first time. The liquid metal was poured from ladles into large cast-iron ingot moulds with an average size of 700 mm in square section and 1.5–2 m in length. Such an ingot would weigh about 7 tonnes. After solidifying, the ingot was stripped from the mould, reheated and then reduced in size by hot-rolling in a primary (blooming) mill to give billets about 100 mm in section. The billets were sheared into 3 to 4 m in length, and they formed the starting material for rolling into bars, beams, rods and strips [17].

This type of billet production persisted until the *1960*s, when a profound change occurred with the development of continuous-casting machines. With liquid steel going directly from the furnace into the casting machine, there was no need to pour large ingots or to reheat them with heavy energy requirements. Nor were the very expensive blooming mills required for reducing the ingots to forms that were produced directly by casting. Continuous casting was first used for non-ferrous metals in the 1930s, and in the early *1950*s, experiments were undertaken with it at steel plants in Britain, the United States and the USSR. The first production plant using continuous casting was operated at Barrow, England, by the United Steels Company. In *1965*, 2% of total steel production was continuously cast; by *1970*, this had risen to 5%, and, by *1990*, 64% of all the steel produced worldwide was continuously cast (in Japan, it was more than 90%) [17].

Continuous casting was partly responsible for a new type of steel plant that developed after 1970 – the so-called mini-mill. In this plant, steel was made in an electric arc furnace using an all-scrap charge and was then continuously cast into small-diameter billets for rolling into rods or drawing into wire. Mini-mills were built in industrial regions, where scrap arises, whereas the location of conventional steel plants remained linked to the availability of iron ore and low-cost energy [17].

1.4.1 Forging

Forging is a metalworking process in which metal is shaped by applying compressive forces, typically using a hammer or press. Due to the ever-increasing size of ingots in the late nineteenth century, large hammer forges were developed, simulating the early blacksmiths' hammering action, which were followed by press forges, first built in Britain in *1861* and introduced into the United States by *1877*, in order to accommodate considerably large components. The mechanisms applied therein are quite simple: the upper forging die pressing against the component (ingot) which is situated on the lower anvil by means of a hydraulically operated piston (Steel – Forming and casting, 2020).

1.4.2 Foundry

A foundry is a factory or workshop where metal is melted and cast into specific shapes by pouring it into pre-shaped moulds. In the 1800s, the development of the crucible process meant that steel castings could be produced for the first time at an industrial scale. *From 1824*, steel products were being cast in Germany and Switzerland, and *by 1855*, steel gear wheels were cast in Sheffield, UK, closely followed by the United States, where the production of steel castings started in *1871* in Pittsburgh [17]. The crucible process was eventually replaced as the chief melting method in *1893*, when the Tropenas converter was invented in Sheffield, UK, after which, in *1907*, electric melting in acid-lined furnaces was pioneered in Switzerland. Electric furnace melting is currently used industry-wide for making steel castings [17]. *In the 1920s,* X-ray methods for assessing the soundness of steel castings were first applied in the USSR. During the period 1924–1928, international standards for moulding materials, such as moulding sand, were published in the United States, and magnetic crack detection methods followed *in the 1930s* [17]. In 2019, 1869.9 million tonnes of steel was produced – up from 770 million tonnes in 1989 and starting with a capacity of 30 tonnes per furnace in 1920. A truly extraordinary development! [39].

1.4.3 Who and where are now the biggest steel producers?

The Wirtschaftsvereinigung Stahl [40] is the geopolitical association of the steel industry in Germany, with headquarters in Düsseldorf, and in their publication 'Fakten Stahlindustrie 2014', they have published a series of helpful graphs, courtesy of worldsteel [41], which give an overview of the steel industry's data and developments. The World Steel Association (WSA, worldsteel), a not-for-profit organisation with headquarters in Brussels, represents steel producers, national/regional steel industry associations as well as steel research institutes. Their member-base represents c. 85% of global steel production.

1.4.4 Which industries is steel being produced for?

Allwood et al. [42] produced a magnificent report which gives an overview of the different industries for which steel is being produced as the most used metal on the planet. For each living person, worldwide, over 200 kg of liquid steel is being produced every year. Figure 1.1 demonstrates the year 2008 'flow' of steel within the world economy. The sheer volume of steel production has significantly risen since 2008, but the proportions of the flow have remained similar.

Four key industries, for which steel is being produced, have been identified and shown in this illustration:

A) Over 50% is being used in the construction industry (596 million tonnes/year)
B) The manufacture of metal goods, such as packages, appliances and others (177 million tonnes/year)
C) Industrial equipment (mechanical/electrical) (176 tonnes/year)
D) 139 tonnes/year being used for the production of vehicles

An estimated 67% of liquid steel produced is made from iron ore, and the remainder is made from recycled metal/scrap. Unfortunately, at present, more than half of this scrap results from the manufacturing process itself, rather than from degraded goods.

Every year, 25% of all the finished steel made is being cut off and recycled, because final users want components (such as refrigerators) and not intermediate products (coils of strip steel).

The world population [43] stands at approximately 7.7 billion people today compared with less than 1 billion in c. 1800. This immense increase in human beings populating our planet, alongside the ignorance of how to build a sustainable society, may jeopardise living standards for future generations. The idea of a sustainable society was an unknown concept until its formal definition in 1987 with the Brundtland report, where it was declared to be a concept, instated by an informed society, which was developed in a balanced way, considering both current and future generations' needs [44].

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