

| The Steel Story

| Tracing steel's
development from
2,000 BC to the
innovations of today.





The Steel Story

The World Steel Association (worldsteel) is one of the largest and most dynamic industry associations in the world, with members in every major steel-producing country. worldsteel represents steel producers, national and regional steel industry associations, and steel research institutes. Members represent around 85% of global steel production.

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Detail of India from Ptolemy's world map. Iron was first found in meteorites ('gift of the gods') then thousands of years later was developed into steel, the discovery of which helped shape the ancient (and modern) world

Steel before the 18th century

Amazing steel

Steel is one of the world's most essential materials. It is fundamental to every aspect of our lives, from infrastructure and transport to the humble tin-plated steel can that preserves food. With steel, we can create huge buildings or tiny parts for precision instruments. It is strong, versatile and infinitely recyclable.

The rise of steel began with the 19th century Industrial Revolution in Europe and North America. Yet steelmaking isn't new. Master craftsmen in ancient China and India were skilled in its production. However, it is only in the past 200 years that science has revealed the secrets of this remarkable material.

Today, steelmakers know how to combine the exact mix of iron, a small percentage of carbon and other trace elements to produce hundreds of types of steel. These are then rolled, annealed and coated to deliver tailor-made properties for innumerable applications.

This book traces major milestones in the history of steel, highlighting some of the many inventors, entrepreneurs and companies that have shaped its development.

Steel has an exciting past and an even more exciting future. Steelmakers continue to reduce the energy required to make steel. Modern high-strength steels provide more strength with less weight, helping reduce the emissions of carbon dioxide of end-products such as cars. And because steel can be so easily recycled, supplies will remain abundant for generations to come.

A happy discovery

The industrialisation of steel production in the 19th century has helped build our modern world, but the origins of steelmaking go back thousands of years. Ever since our ancestors started to mine and smelt iron, they began producing steel.

More than 4,000 years ago, people in Egypt and Mesopotamia discovered meteoric iron and used this 'gift of the gods' as decoration. But it was another 2,000 years before people began producing iron from mined iron ore. The earliest finds of smelted iron in India date back to 1800 Before Common Era (BCE). The Hittites of Anatolia began smelting iron around 1500 BCE. When their empire collapsed around 1200 BCE, the various tribes took the knowledge of ironmaking with them, spreading it across Europe and Asia. The Iron Age had begun.

However, iron is not steel. Iron Age metal workers almost certainly discovered steel as an accidental by-product of their ironworking activities. These early smiths heated iron ore in charcoal fires, which produced a relatively pure spongy mass of iron called a 'bloom' that could then be hammered (**wrought**) into shape.

These early smiths would have noticed that when iron was left in the charcoal furnaces for a longer period, it changed. It became harder and stronger: qualities they undoubtedly recognised as valuable. They would also have noticed that these qualities improved with repeated heating, folding and beating of the material as they forged the metal.



Iron Age metal workers almost certainly discovered steel as an accidental by-product of their activities

Ancient craft



One of the earliest references to steel-working comes from Greek historian, Herodotus, referring to a bowl inlaid by Glaucus of Chios in the seventh century BCE: "A great bowl of pure silver, with a salver in steel curiously inlaid. Glaucus, the Chian, made it, the man who first invented the art of inlaying steel."

New techniques

Having discovered steel and its superior qualities, Iron Age craftsmen transformed it into tools and weapons such as knives. Soon, new techniques were developed, such as quench hardening – the rapid cooling of the worked steel in water or oil to increase its hardness. An archaeological find in Cyprus indicates that craftsmen were producing quench-hardened steel knives as early as 1100 BCE.

Nonetheless, in the ancient world, steelmaking remained a lengthy and difficult process, and the rare steel items produced would have been highly prized.



The East India Company's port in Bombay, India in the 18th century



A Japanese Buddhist temple bell

A global industry begins

Iron Age steelmakers did not understand the chemistry of steel. Its creation held many mysteries and the final result depended on the skill of individual metal workers. First among these were the craftsmen of southern India. As early as the third century BCE, they were using crucibles to smelt wrought iron with charcoal to produce 'wootz' steel – a material that is still admired today for its quality.

Chinese craftsmen were also manufacturing high-quality steel. It seems that the Chinese had something similar to the [Bessemer process](#) as early as the second century BCE, which was only developed in Europe in the 19th century. Steel agricultural implements were widely used in the Tang Dynasty, around 600-900 CE.

Moreover, with expertise came trade. The skills of traders in India and China created an international market in steel. Many historians believe that the famous Roman natural scientist and writer Pliny the Elder was referring to China when he described 'Seres' as the best source of steel in the world. And Damascus swords, celebrated for their exceptional quality, were made of wootz steel from India.



Iron is reheated to reduce its brittleness

Legendary swords

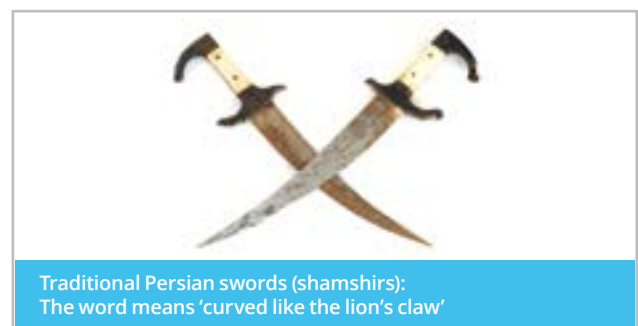
Much of the demand for early steel was driven by warfare. Imperial armies, including those of China, Greece, Persia and Rome, were eager for strong, durable weapons and armour. Among others, the Romans learnt how to **temper** work-hardened steel to reduce its brittleness by reheating it and allowing it to cool more slowly.

By the 15th century, steel was well established worldwide. Swords in particular took full advantage of steel's unique properties, the blades being tough, flexible and easily sharpened. From Damascus and Toledo swords to the katanas wielded by Japanese samurai, steel was the material of choice for the finest weapons of their age.

The use of steel was not confined to military purposes. Many tools such as axes, saws and chisels began to incorporate steel tips to make them more durable and efficient. Yet, despite its growing use, making steel remained a slow, time-consuming and expensive process.



The bayonet was first referred to as early as 1611, and it was named after Bayonne in France. This a Spanish bayonet



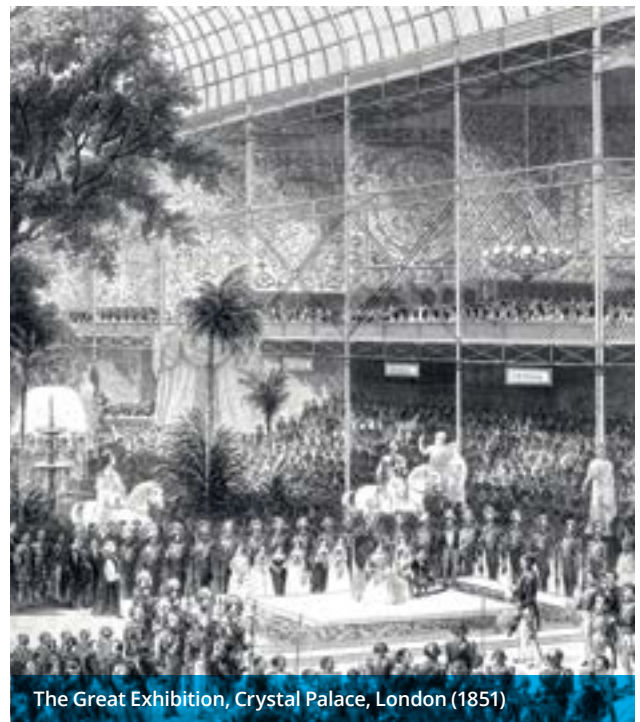
Traditional Persian swords (shamshirs):
The word means 'curved like the lion's claw'



A Japanese katana sword: Traditionally made from a specialised Japanese steel called 'Tamahagane', which consist of combinations of hard, high-carbon steel and tough, low carbon steel

Damascene mysteries

A legend in their own time, Damascus swords were renowned for their sharpness and wavy surface patterning. They were made from wootz steel, which probably originated in Central Asia or Southern India. To this day, nobody has been able to reproduce the characteristics of this remarkable steel.



The Great Exhibition, Crystal Palace, London (1851)

The rise of crucible steel

Over the centuries, the true nature of Damascus or wootz steel and how it was made intrigued metal workers and scholars across Asia and Europe. Many early Islamic scientists wrote studies on swords and steel with extensive discussions of Damascus steel. And from the mid-17th century, a growing number of European travellers such as Frenchman Jean-Baptiste Tavernier incorporated visits to Indian steelmaking sites on their journeys to the East, offering detailed eye-witness accounts in their books and journals.

This interest reflected the continued growth in iron and steelmaking across Europe. As early as the 12th century, technologies such as [blast furnaces](#), already known in Asia, began to emerge. The remains of one of the earliest examples can still be seen at Lapphyttan, in Sweden. Indeed, thanks to its rich iron-ore deposits, advanced production techniques and the purity of its wrought iron, Sweden became a major supplier of high-quality iron to steelmakers across the continent.

Production speed heats up

Mostly, the steelmakers of the time were producing steel using the cementation process, in which wrought iron bars are layered in powdered charcoal and heated for long periods to increase the carbon content in the **alloy**. It was a process that could take days or weeks.

Then in 1740, a secretive yet highly inventive young Englishman called Benjamin Huntsman revealed his new crucible technique to master cutlers in the north of England. Using a clay pot, called a crucible, he was able to achieve temperatures high enough to melt the bars created in the cementation process and **'cast'** (pour) the resulting liquid steel to create steel **ingots** of uniform high quality and in relatively high quantities – at least in comparison with what had gone before. Huntsman's invention was not the final step towards low-cost, high-volume production of high-quality steel. It would take other inventors to achieve that goal. He had, however, provided the impetus for one of the greatest steelmaking centres of the 19th and 20th centuries – Sheffield, England.

Clock springs to cutlery

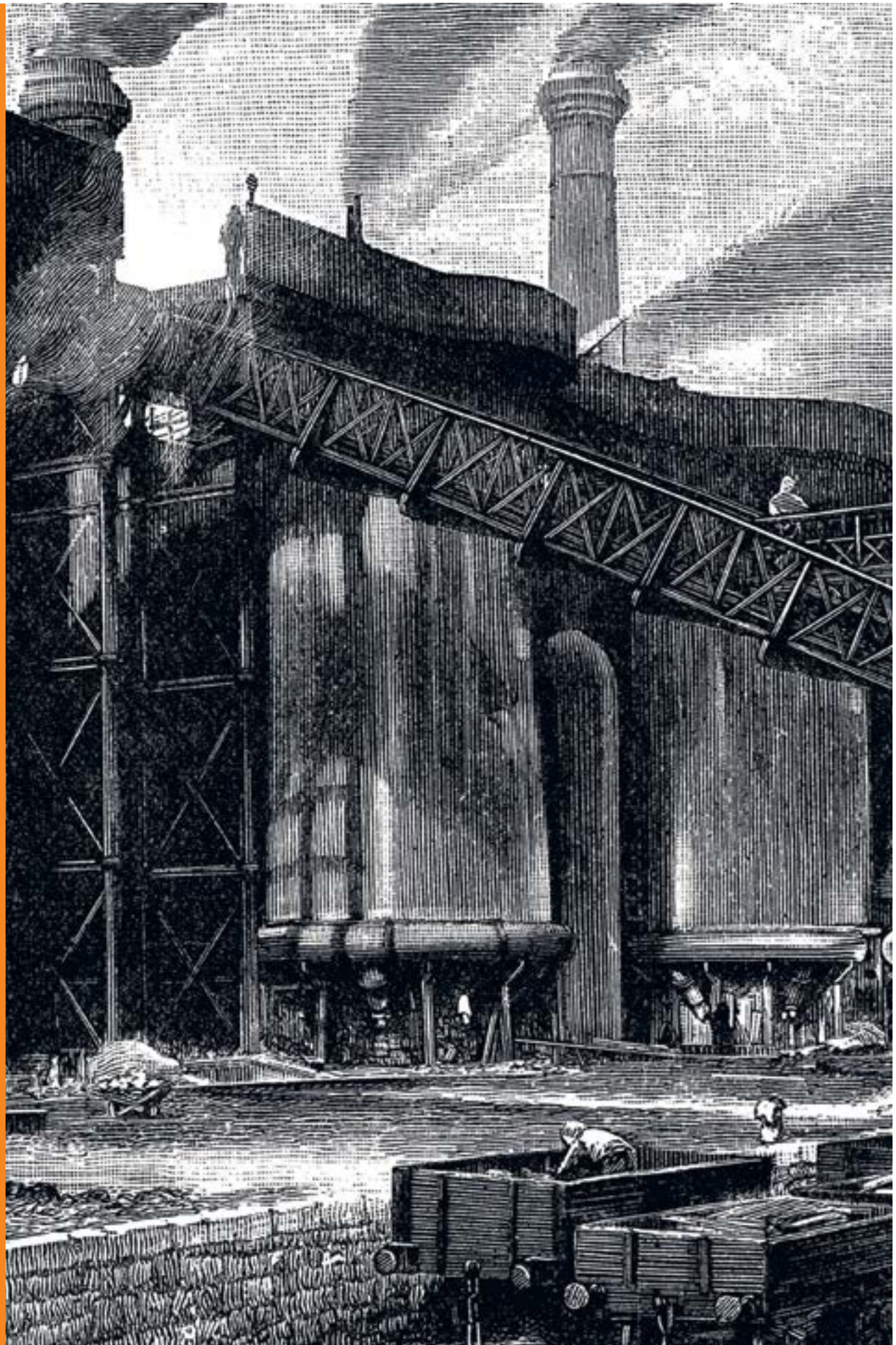


Huntsman's invention began with clock springs. As a clockmaker, Huntsman was dissatisfied with the quality of existing steel parts from Germany, so he set out to make his own steel. Remarkably, when he

first approached the cutlers of Sheffield with his crucible steel, they refused to work with it. Only when they were unsuccessful in trying to block him from exporting it to French manufacturers, did they finally start using it.



Blacksmiths inside a forge – taken from the Illustrated London News, circa 1740



19th century blast furnaces in Lancashire, England

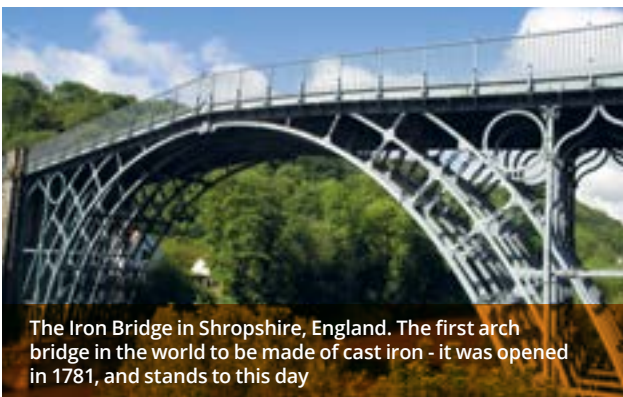
18th to 19th century

Revolution!

Huntsman's development of the crucible process was just one invention of the Industrial Revolution, a time of huge technological creativity. Originating in Britain, the Industrial Revolution led to massive changes in manufacturing, trade and society worldwide. When it began in the 18th century, iron still dominated the industrial landscape. By its end in the early 20th century, steel was king, the metal at the heart of the modern world.

From trees to steam

The Industrial Revolution and modern steel manufacture began with a shortage of trees. Up to the 1700s, British iron and steelmakers used charcoal both in their furnaces and to 'carburise' iron. But with agricultural and industrial expansion, wood became in increasingly short supply. So metalworkers turned to coke, made from coal, as the fuel for reverberatory furnaces, where heat radiated off the walls and roof to create temperatures high enough to melt the ore.



The Iron Bridge in Shropshire, England. The first arch bridge in the world to be made of cast iron - it was opened in 1781, and stands to this day

Then in 1709, Abraham Darby perfected the use of coke in a **blast furnace** to produce **pig iron** for pots and kettles. This new technique helped boost production, leading to further demand for coal and coke. But coal mining had a problem: how to keep underground mines from flooding.

Thomas Newcomen developed a revolutionary solution, the 'atmospheric engine', a forerunner of the steam engine, in 1712, and it changed the world. By 1775, James Watt had created an improved steam engine; by 1804, the first railways had been built. Where industries such as textiles once relied on manual labour, watermills and horses, steam brought mechanisation and mass production.

Building with metal

Steam pumps helped power water wheels, which allowed iron and steel manufacturers to drive their blast furnaces, even in periods of low rainfall. Coke pig iron became plentiful, and iron was increasingly replacing wood as a construction material. In 1778, Darby's grandson built the famous Iron Bridge in Shropshire, England, one of the most innovative structures of the age, which is still functional and in very sound condition.

Meanwhile, steel was providing the hard, sharp edges for many of the tools required by this new era of machine power. It was the material of choice for drill bits, saws and cutting edges of all kinds. These growing applications of iron and steel encouraged further innovation. Soon another inventor, Henry Cort, would set the scene for a vital manufacturing process - the rolling of sheet iron and steel.



Steel plus steam allowed for the vital development of railways

The foundations of the modern world

As the Industrial Revolution progressed, so did demand for iron and steel. These metals were critical to trade and transport. There would be no railways without metal. And shipbuilders too were demanding ever-higher quality metal components. As a supplier to the shipbuilding industry, Henry Cort developed two ground-breaking techniques to meet these needs, patented in 1783 and 1784.

One involved improving the quality of pig iron by stirring the molten melt in a puddling furnace. This reduced the carbon content, so the metal was tougher and less brittle. The second technique involved rolling the hot metal ready for manufacturing into end products. Gentler than traditional hammering, this further added to the metal's strength.

With this combination, Cort set the scene for mass production of vital components for the new industrial world such as tracks for railways. It paved the way for industrial-scale rolling mills and the creation of sheet iron and steel for new applications, such as the building of iron ships.

Steel makes its mark

By the 1800s, large-scale industrialisation was spreading throughout Europe. Pioneers took the latest techniques and technologies with them overseas, bringing industrialisation to North America, Japan and the rest of the world.

At this time, steel was not yet being mass produced. Nonetheless, it was making a major impact in areas such as agriculture. Nowhere was this more apparent than North America, where farmers were turning virgin land into farmable soil.

Above all, steel played a key role in opening up the prairies of the Midwest. [Wrought iron](#) ploughs simply broke in the heavy soils, so a quick-thinking young blacksmith called John Deere created a plough with a steel blade. In the next 50 years, the steel plough and steam-driven equipment transformed agriculture, not just in the US but in Europe as well. Mechanisation had arrived on the land.



An 18th century puddling furnace



The Eiserner Steg steel bridge built in 1868 in Frankfurt, Germany

Pipes and welds

In 1815, Scottish engineer William Murdock is said to have joined together disused musket barrels to form a pipe network for his coal-fired lighting system in London. His initiative marked the start of steel piping, now a fundamental element in oil, gas and water infrastructures. Today's pipes are either seamless, with the centre forced out during production, or have a welded seam along their length, technology that dates to the Mannesmann process, based on cross-roll piercing which, for decades, was used in combination with pilger rolling. Both rolling techniques were invented by the German brothers Reinhard and Max Mannesmann towards the end of the 19th century. In the 1880s, while they were rolling starting material for the family's file factory, the Mannesmann brothers noticed that rolls arranged at an angle to each other can loosen the core of an ingot and cause it to break open. Based on the bold idea of putting this phenomenon to systematic use, they managed to produce a seamless hollow body from a solid ingot – initially by rolling alone. Very soon, however, they optimised the rolling process by using a plug to

ensure more uniform piercing and a smoother inside surface. The need for pipes to be perfectly sealed has helped drive [welding techniques](#), as well as the development of steels that can withstand high welding temperatures without cracking or weakening.

Famous names in steel



Some of today's leading steel companies have their roots in the 1800s. For example, Friedrich Krupp and partners formed the Krupp Company in Germany in 1811. By the end of the century, it was the largest steel company in

Europe and today is part of thyssenKrupp. In Japan, Nippon Steel (today Nippon Steel Corporation) can trace its history back to 1857, when steel was successfully tapped from Japan's first Western-style furnace at Kamaishi.



The Eiffel Tower in Paris, France: Gustave Eiffel's iconic iron lattice masterpiece contains 18,038 pieces of puddle iron and 2.5 million rivets

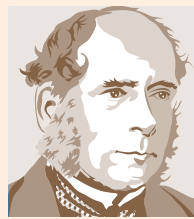
Into mass production

For centuries, steel had remained a 'niche' metal, prized for its toughness and for creating sharp edges, but it was slow and expensive to manufacture. In the 1850s and 1860s, new techniques emerged that made mass production possible.

This transformation is largely associated with the work of one English inventor, Henry Bessemer. Arguably the most influential advance of the later Industrial Revolution, the Bessemer process formed the heart of steelmaking for more than 100 years. Introduced in 1856, it revolutionised the industry with a quick, cheap way to produce steel in large quantities.

At the same time, Carl Wilhelm Siemens, a German national who spent most of his life in England, was developing his regenerative furnace. By recycling the hot exhaust gases from the previous batch of melting, Siemens' process could generate temperatures high enough to melt steel. And by 1865, Frenchman Pierre-Emile Martin had applied Siemens' technology to create the Siemens-Martin **open hearth** process.

The Bessemer converter



Bessemer aimed to create steel by driving the impurities out of pig iron. Air-pumps forced high-pressure air through molten iron in his egg-shaped furnace. Rather than cooling the iron, the air reacted with

impurities such as carbon, manganese and silicon in the iron, causing them to oxidise. This raised the temperature further, igniting even more impurities and producing a violent display with sparks and flames erupting from the converter's open top like a volcano. Fast and cheap, when finally perfected this spectacular process took less than half an hour to turn pig iron into steel.



Although not quite as fast as the Bessemer process, open-hearth techniques allowed for more precise temperature control, resulting in better-quality steel.



A 19th century industrial landscape in Wales by Penry Williams

Ancient technique, modern success

Bessemer was not the first to invent an air-injection process to create steel. Such techniques had been used in ancient China. William Kelly, an American inventor, independently came up with such a process in the 1850s, possibly inspired by Chinese know-how. Kelly subsequently went bankrupt, and even Bessemer struggled to make his process work. It was advice from Englishman Robert Mushet, an expert metal-worker, to blow off all the impurities then add carbon back into the metal that finally led to a high-quality, malleable (rollable) product.

Material of choice

In the course of just two decades, these inventors shaped the modern steel industry. Now, consistently good quality steel was available in high volume and consistent shapes and sizes, perfect for the vast majority of large-scale, heavy-duty applications.

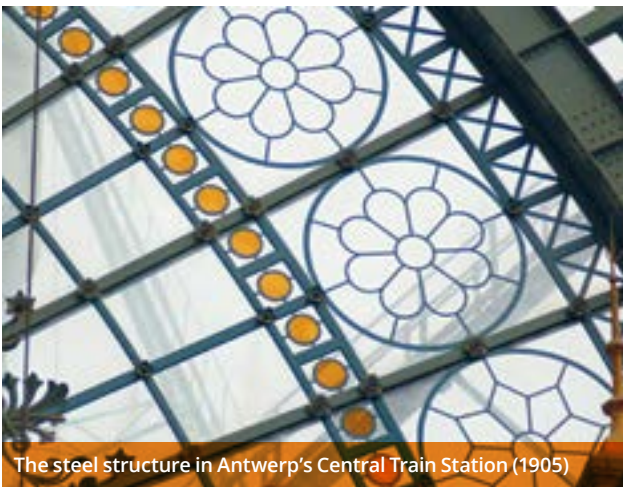
Steel quickly replaced iron in the emerging railways, and all kinds of construction from bridges to buildings. It also enabled the manufacture of large, powerful turbines and generators, harnessing the power of water and steam to drive further industrialisation and usher in the age of electric power.



A steam turbine: steel is an irreplaceable component

Building the future

With the introduction of the Bessemer process, steel became one of the cornerstones of the world's industrial economy. Available in large quantities and at a competitive price, steel soon supplanted iron in buildings where steel framing and reinforced concrete made 'curtain-wall' architecture possible, leading to the first skyscrapers. And in shipbuilding, steel began to replace wrought iron plates. Cunard's SS Servia was one of the first steel liners – complete with another innovation, electric lighting.



The steel structure in Antwerp's Central Train Station (1905)

Britain grew to be the world's largest producer of steel. The bulk of the UK's steel industry was located in Sheffield, where John Deere initially sourced the steel for his ploughs. But by the last decade of the 19th century, America would outgrow Britain to become the largest steel producer in the world, due mainly to the efforts of one man: Andrew Carnegie.

A weaver's son from Scotland, Andrew Carnegie was already a successful businessman in the rail and telegraph industries by the start of the American Civil War in 1861. After the war, the US saw a boom in construction. Railways opened up the 'Wild West' and the cities of America's east coast grew rapidly. And Carnegie was there to meet the demand for iron, and later steel.

Carnegie was a master of efficiency. He was quick to adopt, and improve on, innovations such as the Bessemer process. He is also credited with the vertical integration of all raw materials suppliers and was involved in several early steel projects. For example, his Keystone Bridge Company supplied the steel for one of the world's first steel bridges, the Eads Bridge across the Mississippi at St Louis, completed in 1874 and still in use today.

The Carnegie steelworks also provided a first job for Charles Schwab, who went on to run the Bethlehem Steel Company, one of the US' largest and most famous 20th century steelmakers. And across the USA, this was an age of steel construction 'firsts'. New York's Brooklyn Bridge, the first steel wire suspension bridge, opened in 1883. The world's first steel-framed skyscraper, the Home Insurance Building in Chicago was constructed by William Le Baron Jenney in 1884-1885. The Iron Age was at its end and the age of steel had truly begun.



Brooklyn bridge, New York, USA (1883). This was the longest suspension bridge in the world until 1903, and the first steel-wire suspension bridge



An old-style skyscraper, built before steel became commonplace in skyscrapers' construction

Andrew Carnegie



Andrew Carnegie's life is the classic 'rags-to-riches' tale. Born in Dunfermline, Scotland, his family emigrated to the US in 1848. Carnegie started work aged 13, earning just 20 cents per day. At 18, he was employed by the Pennsylvania Railroad Company, where he advanced rapidly up the organisation while learning much about business. In 1870, he founded the Carnegie Steel Company, which grew to become the largest and most profitable industrial enterprise in the world by the 1890s.

At age 66, Carnegie sold the company to financier, banker and philanthropist J.P. Morgan, who developed many improvements in mill design and rolling of steel that were built on and improved over the decades to come – Carnegie, meanwhile, devoted the rest of his life to investing his wealth in projects for the public good. These ranged from libraries to schools and hospitals and included the Carnegie Institute of Technology, now part of the Carnegie Mellon University.



A 1950s Cadillac Eldorado Chrome Grille in San Francisco, California, USA

20th century global expansion, 1900-1970s

The steel age

By the dawn of the 20th century, steelmaking was a major industry and science was increasingly unlocking the mysteries of steel. A British 'gentleman scientist' named Henry Clifton Sorby created a sensation by putting metal samples under a microscope. His pioneering work revealed steel's secret – it gained its strength from the small, precise quantities of carbon locked within the iron crystals.



Pyrite mineral on mine rock

This was also an age of great industrialists. In the US, J.P. Morgan bought out Andrew Carnegie's steel business to form the United States Steel Corporation in 1901, which founded the city of Gary, Indiana in 1906 as the home for its new plant – Gary was named after Elbert Henry Gary, founding chairman of US Steel. Morgan had learned from Carnegie that integrating all parts of the manufacturing process into one single organisation could lead to efficiencies in process and scale.

Manufacturing processes evolved too. The open-hearth process gradually replaced the Bessemer process as the primary method for steel production. Although slower, this drawback was also its advantage – plant chemists had time to analyse and control the quality of the metal during the refining process, resulting in stronger grades of steel.

With greater understanding of the properties of steel, steel [alloys](#) became more widespread. In 1908, the *Germania*, a 366-tonne yacht built by the Friedrich Krupp Germania shipyard had a hull made of chrome-nickel steel. And in 1912, two of Krupp's German engineers, Benno Strauss and Eduard Maurer, patented stainless steel, the invention of which is in fact usually credited to Harry Brearley (1871-1948), a Sheffield-born English chemist who, during his work for one of the city's laboratories, began to research new steels that could better resist the erosion caused by high temperatures, and examine the addition of chromium, which eventually resulted in the creation of what is probably the best-known alloy of all.

The impact of war

The 20th century's two world wars had huge consequences for steelmaking. Like other heavy industries, steelmaking was nationalised in many countries due to demands for military equipment. Steel was required for the railways and ships that carried troops and supplies.

Military vehicles and particularly the tank also relied heavily on steel. From their invention until the end of the Second World War, tanks were protected by steel plates with a uniform structure and composition known as rolled homogenous armour (RHA). This type of armour was so universal that it became the standard for determining the effectiveness of anti-tank weapons.



A Soviet T-34 tank (produced between 1940 and 1968)



A 1950s American kitchen: Steel played an important role in the post-war labour-saving devices that became increasingly available and inexpensive

Welcome to the white-goods era

After the austerity of the Second World War, trade and industry revived. Steel that once went to make tanks and warships now met consumer demand for automobiles and home appliances.

Populations boomed and so did construction. As more people moved into cities, buildings became larger and taller, and huge quantities of steel were required for girders and reinforced concrete.

Growing prosperity and technological innovation transformed everyday life. By the 1960s, mass-produced electrical appliances became increasingly accessible to millions of consumers.

These included refrigerators, freezers, washing machines and tumble dryers, etc. And the iconic shipping container – designed in 1955 and made of steel – provided a strong, safe way to transport all these goods by ship, road and rail.

Obviously, the automobile quickly became a hugely popular mass-consumption item, transforming the landscape and leading to the development of the oil and gas industry, a process that involved all types of steel products.

Stronger steel

New technologies and infrastructures drove demand for new kinds of materials with very specific mechanical properties. Steelmakers around the world responded to the challenge, launching developments that would reveal steel's almost infinite versatility. By adding carefully controlled quantities of different elements to the melted iron ore, they began to develop new high strength, low alloy (HSLA) steels.

The oil and gas industry had special needs. Giant pipelines across baking deserts, frozen wastes, or under the sea, need to be strong and tough. They must also have excellent weldability, so there is no weakness at the joints between sections. In this case, an HSLA steel with manganese and traces of other elements delivered all the required properties.



Industrial steel pipelines

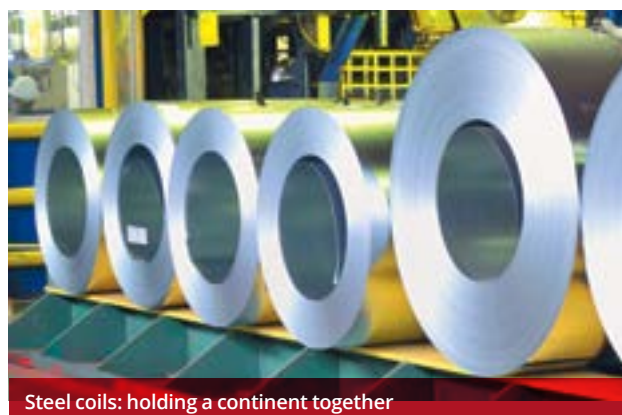
From these beginnings in the 1960s, the range of HSLA steels has grown enormously. They are used in everything from bridges to lawnmowers. Above all, they offer a much greater strength-to-weight ratio than traditional carbon steel. Typically, they are around 20-30% lighter than carbon steels, with the same strength. This property has made them especially popular with carmakers, allowing cars to be strong and safe, yet also light and fuel efficient.



Strengthening international bonds

While steel was providing the foundations of modern society, the steel industry was acting as a focus for new relationships between countries. In 1951, France, West Germany, Italy and the Benelux nations joined together in the European Coal and Steel Community (ECSC).

The community created a 'common market' to drive economic expansion, promote industry and raise living standards. With its focus on free movement of products, the European Coal and Steel Community was the first step on a journey that ultimately led to the creation of the European Union.



Steel coils: holding a continent together

From flame to electricity

In the mid-20th century, steelmaking advanced on many fronts. **Basic oxygen steelmaking** and **electric arc furnaces** transformed the main production processes, making them faster and more energy efficient. They even allowed manufacturers to reuse scrap as input material.

Along with introducing new primary techniques, steelmakers also improved on traditional techniques of casting and rolling to create sheets, shapes and steel to precise customer requirements. Some of these developments came from Europe, the USA and Russia. But new steelmakers, especially in Japan and Korea, quickly developed their own innovations that in turn inspired steelmakers worldwide.

What exactly were these new techniques? The first – basic oxygen steelmaking – is essentially a refined version of the Bessemer converter, which uses oxygen rather than air to drive off excess carbon from **pig iron** to produce steel. The process was invented by a Swiss scientist named Robert Durrer in 1948, and was then further developed by Austrian company VÖEST AG (today voestalpine AG). It is also known as the Linz-Donawitz (LD) process, after the Austrian towns in which it was first commercialised.

Most importantly, the process is fast. Modern basic oxygen furnaces (BOFs) can convert an iron charge of up to 350 tonnes into steel in less than 40 minutes – compare this with the 10–12 hours needed to complete a ‘heat’ in an open-hearth furnace.

Making the most of scrap

Seeing the benefits of speed and reduced energy consumption, manufacturers soon began to replace open-hearth furnaces with BOFs. But in the 1960s, scrap from vehicles, household appliances and industrial waste became a significant, and cheap, resource. The question was, how to reuse it? In a BOF, up to 25% of the charge can be scrap steel.

So, innovative steelmakers turned to an old technique and brought it up to date. Electric arc furnaces (EAFs) had first appeared at the end of the 19th century. However, until the 1960s, they were primarily used for speciality steels and alloys.

Now, with abundant scrap, EAFs were suited for larger-scale production. Unlike a BOF, an EAF does not need hot metal – it can be fed with cold or preheated scrap steel or pig iron. The furnace is charged with material and electrodes are lowered into it, striking an arc and thereby generating high enough temperatures to melt the scrap. As with a BOF, the process is quick, typically taking less than two hours. Moreover, EAF plants are relatively cheap to build, which was an important advantage for American and European industries still recovering from a world war.



Scrap recycling is very profitable and also helps reduce greenhouse-gas emissions and conserve energy and natural resources



An electric arc furnace (EAF)

Continuous casting

In addition to these new ways to produce raw steel, new ways to cast (pour) the molten metal into moulds emerged. Up to the 1950s, steel was poured into stationary moulds forming ingots (large blocks) that were then rolled into sheets, or smaller shapes and sizes. In continuous casting, liquid steel is fed continuously into a mould in a conveyor belt type process, creating a long **strand** of steel. As the strand emerges from the mould, it is cut into slabs or **blooms**, which are much thinner than traditional ingots and thus easier to roll into finished and semi-finished products.

Steels for every purpose

Producing raw steel and moulding it into ingots or slabs is just the first step in industrial steelmaking. These huge blocks must be rolled to reduce their thickness and form them into the required shapes and sizes. At this stage the steelmaker's skill brings yet more versatility to the metal.

Craftsmen in ancient times knew that steel's properties depend not only on its chemical composition, but also on how it is heated, cooled, hammered and rolled. Modern steelmakers have mastered these processes to an amazing degree. Today, steelmakers can offer customers almost any set of characteristics they request, from ultra-strong steels to foils as thin as tissue paper.

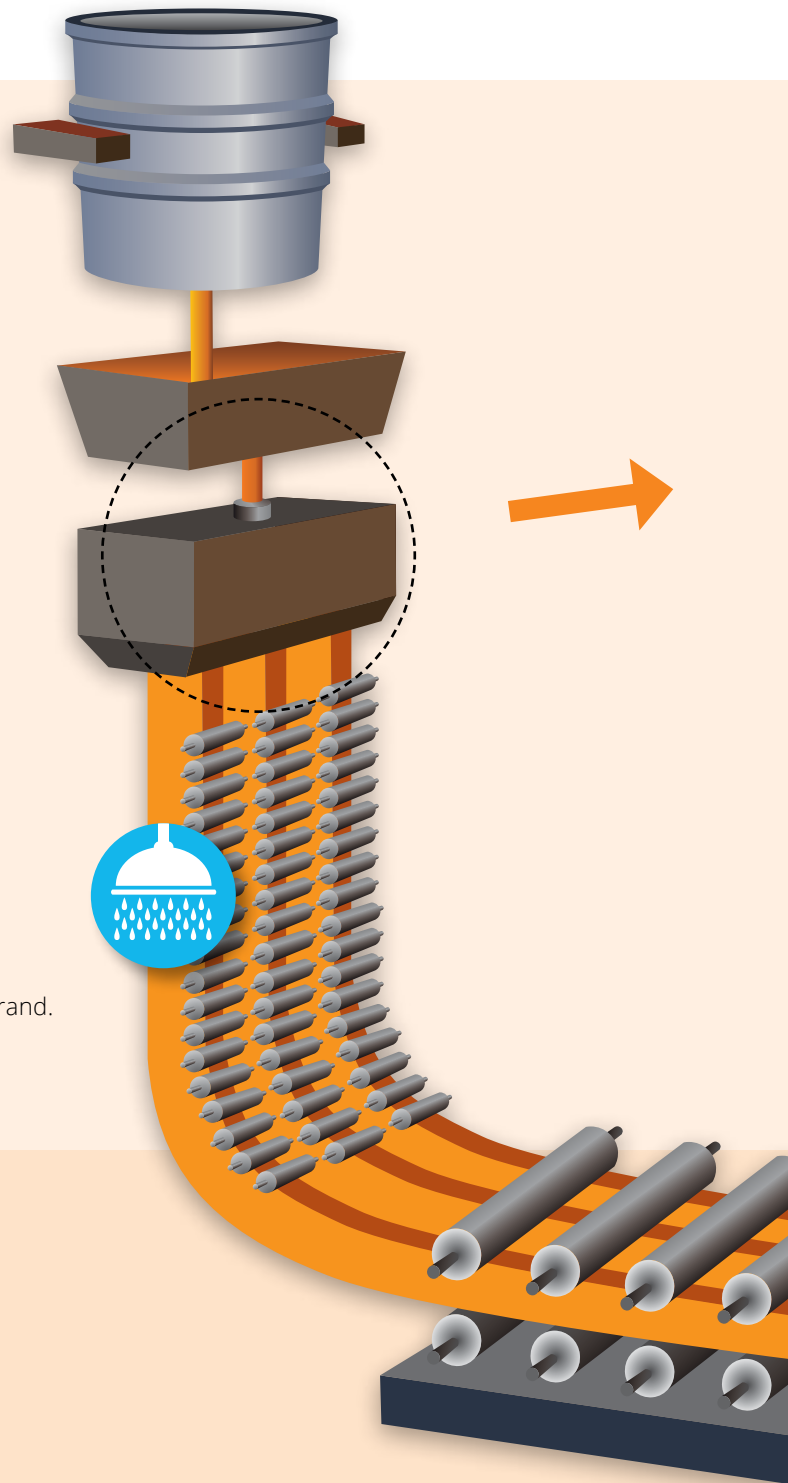


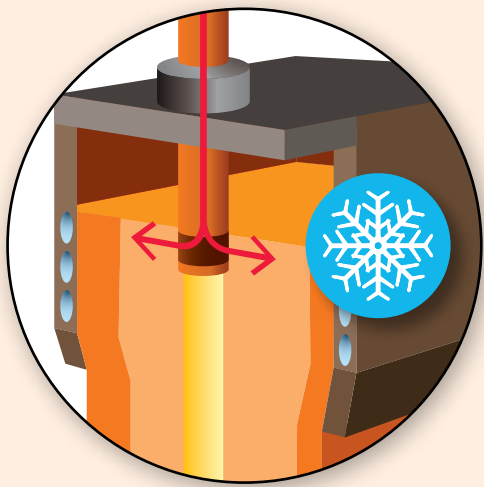
Steel ingots, cast into shapes that are suitable for further processing

The continuous casting process

The molten steel is tapped from the bottom of the ladle into an intermediate container known as the tundish. The temperature of the melt is below 1,600°C.

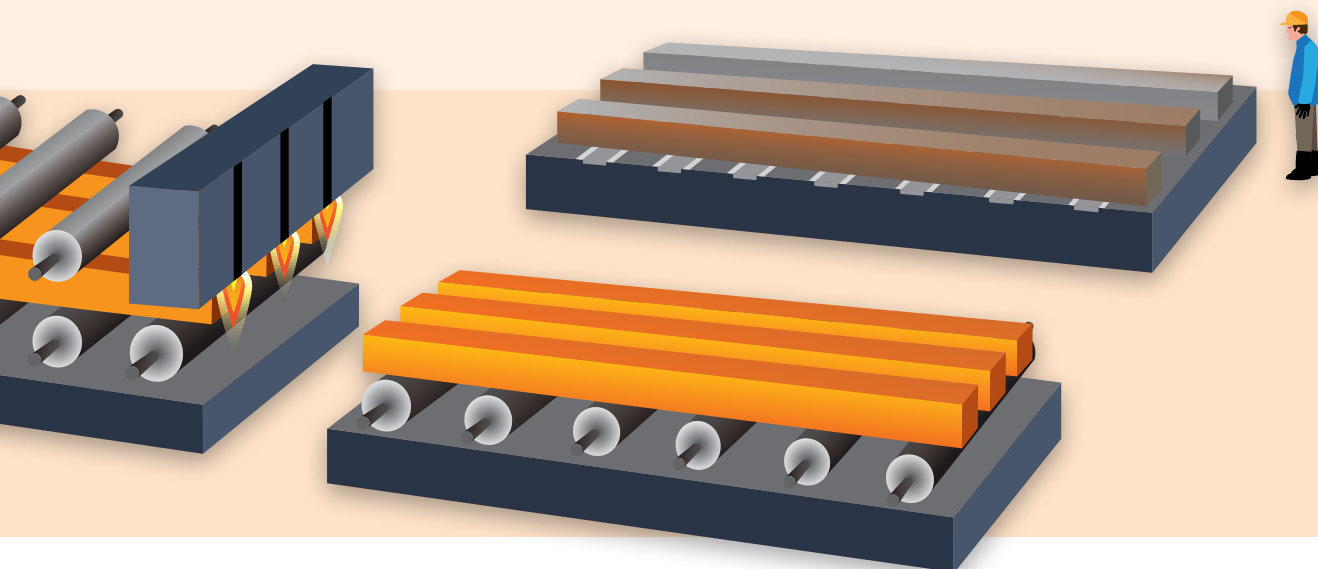
Cooling continues by quenching with water along the whole of the strand.





The **open mould** consists of four water-cooled plates between which hot steel slides. A solidified shell is formed during casting. The casting temperature is around 1,540°C.

The **steel** is glowing hot but has solidified all the way through when it is cut into billets by means of oxygen lances. The temperature is 1,000°C. Every billet is marked before it is placed on the cooling bed.



Finished to perfection

The complex task of rolling ingots or slabs begins with 'roughing'. Giant rollers make a number of passes to reduce the thickness of the material – for example, taking a slab down from around 240mm to 55mm or less. Next come numerous finishing rolling steps before recoiling. Then the material can take a number of routes, one being pickling to remove the scale, followed by cold rolling.



Hot rolling: A metal forming process in which metal stock is passed through a pair of rollers

Both hot and cold processes make the material thinner; they also transform the crystal structure of the iron and other elements in the metal. That in turn affects the properties of the steel. Hot rolling increases ductility, toughness and resistance to shock and vibration. Cold rolling adds hardness and strength.

However, adjusting the mechanical properties of the metal does not end there. Often, steel will be annealed: that is to say, reheated to around 800°C and slowly cooled. For example, cold rolled steel has been work-hardened, making it brittle. Annealing softens the metal enough to retain sufficient hardness, while allowing it to be formed into products such as car parts. Other processes such as quenching (rapid cooling) and tempering (re-heating after quenching) provide further control over each grade of steel's precise mechanical properties.

Finally, the steel may be coated to protect it from rust and corrosion – this is especially important in applications such as shipbuilding, bridges and railways where the metal can be exposed to heat, cold, salty seawater and rain. Hot dip galvanising is widely used to coat steel with a layer of protective pure zinc or a zinc-aluminium mix. For other applications, the surface may be pre-primed to take paint, or treated for UV and scratch resistance, or given a dedicated treatment or coating from a vast palette of colours that add functional or decorative finishes.



A crude-oil tanker



St. Johns Bridge in Portland, Oregon, USA, is a steel suspension bridge, opened in 1931

The mini mills transformation

The rise of EAFs in the 1960s paved the way for **mini mills** and a significant change in the steel industry. Traditional **integrated mills** based on BOFs require a blast furnace to supply molten iron as input. They are large and costly to build. Mills based on an EAF are different. Using scrap or direct reduced iron (DRI) or pig iron as input materials, they are generally smaller and simpler to build and operate – hence the name ‘mini mills’. They can also be set up with a smaller level of capital, and that opened the door to a new breed of entrepreneurs.

In Europe, German entrepreneur and steelmaking innovator, Willy Korf, broke new ground in the steel industry by establishing an EAF plant on an island in the Rhine, near Strasbourg, France in 1968. Just a

Galvanising innovation



Steel is used in hugely demanding applications from shipbuilding to pressure vessels in nuclear power stations. It is also trusted by millions of people to keep a roof over their head.

Galvanised corrugated roofing is a familiar sight worldwide. Galvanisation has been known since the 19th century, but in the 1930s, a young Pole, Tadeus Sendzimir, invented a way to galvanise steel in a continuous production process. His Sendzimir Company also became a world leader in cold rolling, and the steel skin for the Apollo spacecraft was produced in one of its mills.





White-hot steel pours from a 35-tonne EAF, Allegheny Ludlum Steel Corp., Brackenridge, USA

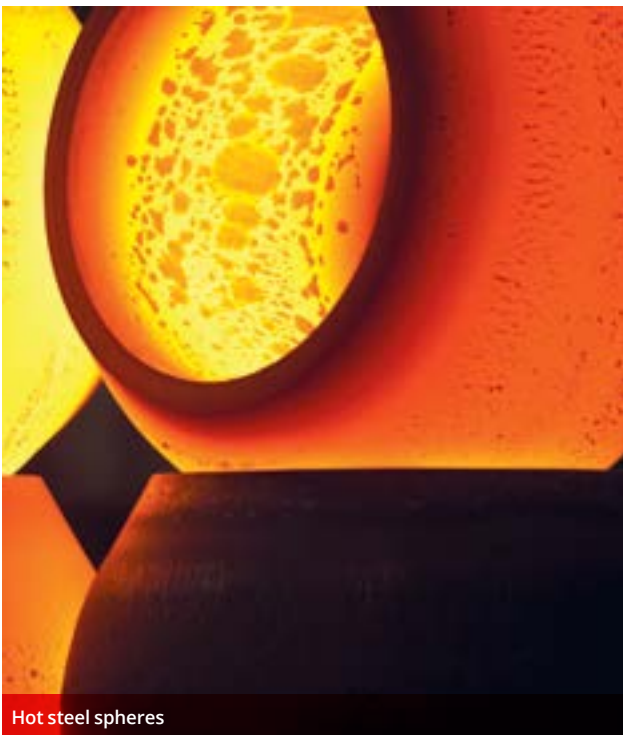
year later, Korf took the technology to the United States, setting up the Georgetown Steel mini mill in South Carolina.

Around the same time, US metallurgist Ken Iverson was building Nucor's first mini mill at Darlington, also in South Carolina.

Within two years, Iverson had turned the company around, making it profitable and a leader in its field. His faith in the potential of mini mills proved well-founded and for the next 16 years achieved rapid and consistent growth.

Iverson broke down hierarchical structures and emphasised teamwork, performance-based compensation, shared benefits and community involvement.

These innovations in management structures were also matched by taking the lead in the development of EAF technology, which at the time was undergoing a revolution. In particular, they moved EAF technology closer to the high-value end of the steel product range, producing high-quality flat products from scrap feed materials.



Hot steel spheres



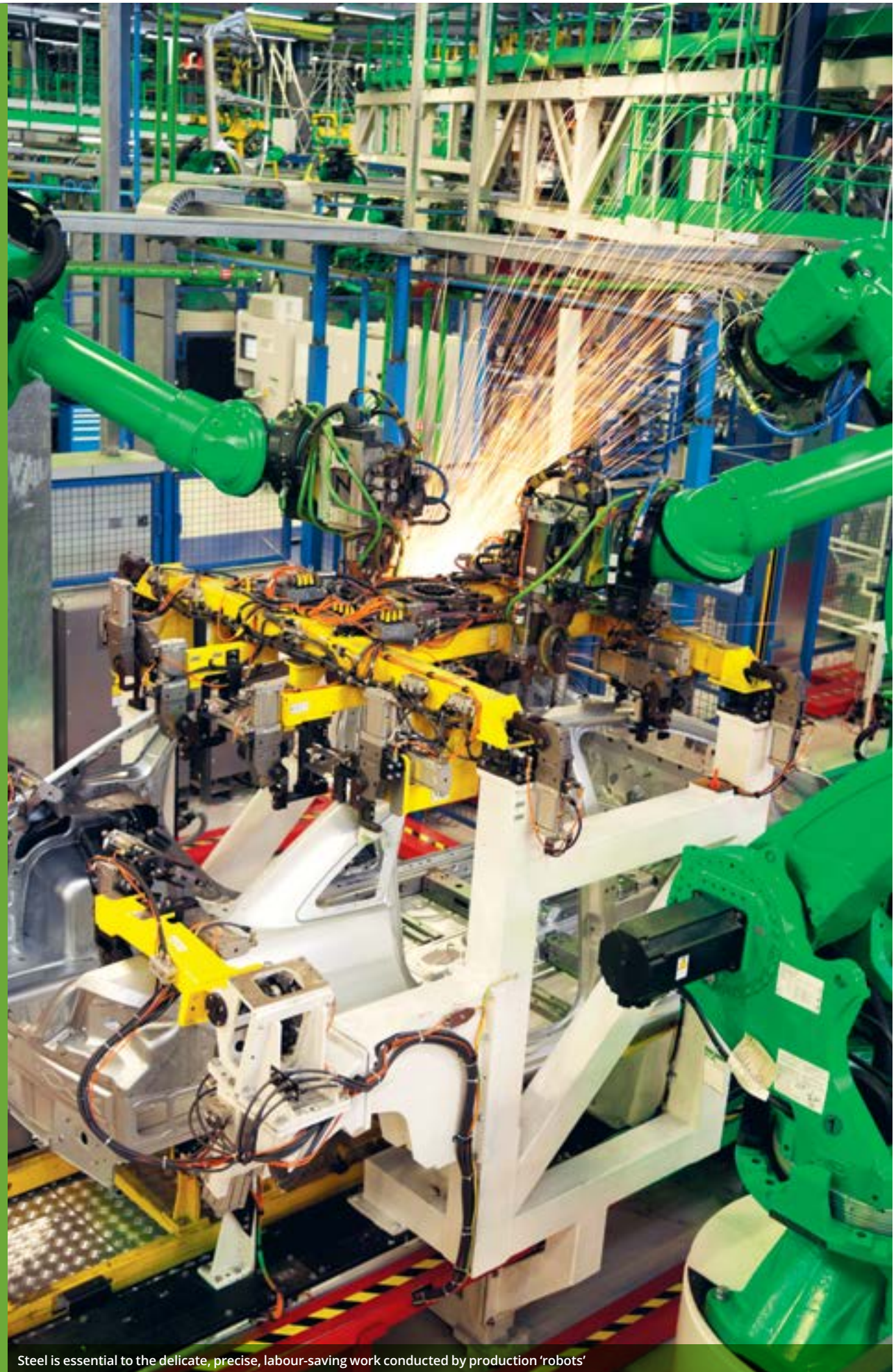
Steel profile laser cutting



Recycling ahead of its time

Mini mills are effectively recycling plants. They take in scrap metal and convert it into useful steel. Today, the importance of this is clear, not just commercially but for the benefit of the planet, as it saves the use of natural resources/raw materials. In the 1960s, however, the concept of 'sustainability' was only just starting to emerge.

The question of how far the planet could sustain growing populations hit the headlines in 1970, when a group of politicians, academics and industrialists published *The Limits to Growth*. Among the group was Dutchman Max Kohnstamm, a former secretary of the High Authority of the European Coal and Steel Community. Although the report's findings caused controversy at the time, governments and industry bodies worldwide now agree that manufacturing's future depends on efficient, sustainable use of energy and resources. It was complemented by the Brundtland Commission report *Our Common Future*, in 1987, which addressed similar themes.



Steel is essential to the delicate, precise, labour-saving work conducted by production 'robots'

End of 20th century, start of 21st

Going for growth: Innovation of scale

While mini mills were emerging in the USA and Europe, Asia saw innovation in scale and output. Pursuing rapid growth in the 1960s and 1970s, Japan, followed closely by South Korea, developed massive state-of-the-art integrated facilities. These generated high-quality flat products from coils to coated and galvanised sheets, targeted at sectors such as automotive and appliance manufacturing.

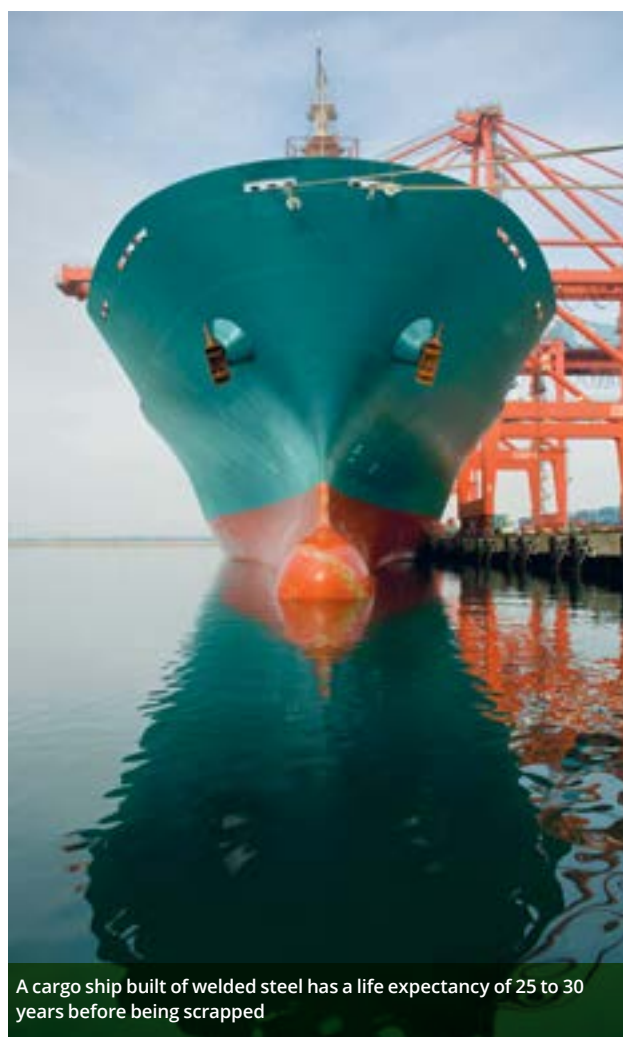
Unlike older steelmaking countries, neither Korea nor to a lesser extent Japan had a legacy of open-hearth furnace production. Instead, partly due to a lack of domestic scrap, they advanced directly to innovative BOF technology, building giant blast furnaces to supply the pig iron input.



A steel coil galvanising production line

Early adopters

Japanese producers also adopted continuous casting on a massive scale, further increasing output and reducing costs. Korea took the same path, and today virtually all its output is produced this way. At the same time, both countries seized on computer technology as a means of managing their vast



A cargo ship built of welded steel has a life expectancy of 25 to 30 years before being scrapped

operations. Fuji Steel introduced analogue computers as early as 1962, and the microchip revolution of the 1970s fuelled the use of electronics for process and information control.

With electronic technology, producers could handle complex scheduling and meet the demand for a wider range of products as well as stringent quality requirements. Modernisation also changed working practices. Automated equipment meant plants were much safer and could be operated by smaller numbers of workers, improving efficiency and reducing risks.

Continuing innovation

Old or new, Japan and Korea's companies are committed to innovation. Created in 1970 from the merger of Yawata Steel and Fuji Steel, Nippon Steel Corporation can trace its roots back to 1857. Now Japan's biggest steelmaker, it invests extensively in continued process improvement and in ensuring steelmaking plays its role in respecting the planet.



In South Korea, POSCO began life only in 1968 during the country's rapid economic expansion. By 1985, its first plant in Pohang was producing 9.1 million tonnes of crude steel per year and work had begun on a second in Gwangyang – now one of the world's largest steel mills.

Enter the entrepreneurs

Flourishing large-scale production in Japan and Korea contrasted with trends elsewhere. By the 1970s integrated steel production in Europe and North America suffered from outdated technology, overcapacity, rising labour and raw materials costs, and competition from alternative materials such as aluminium and plastics. In countries where production was nationalised, governments were unwilling to invest against a backdrop of declining markets, so equipment and processes failed to evolve.

As the 1980s progressed, economic conditions presented challenges for large plants worldwide. But as the industry looked for a way ahead, a wave of innovation in mini mills and privatisation opened up new opportunities for steel entrepreneurs.

Mini mills expand into new markets

Initially mini mills produced low-value rebar steel (concrete reinforcing bars). With small melting chambers and input of scrap, they could not compete with high-quality products from integrated mills.

However, as the rebar market became saturated, mini mill owners developed ways to produce higher value structural steel. In 1987, Nucor pioneered the use of an EAF and compact strip production (CSP) from German company SMS SchloemannSiemag to produce



The invention of reinforced concrete in the 19th century revolutionised the construction industry

sheet steel. By starting with thin slabs of just 40-70mm, CSP dramatically reduced the time and number of rolling stages needed to produce steel as thin as 1mm. And for mini mills, it meant a cost-effective way to enter the sheet-steel market.



A large hot orange steel sheet being rolled in a steel mill

New technologies also enabled them to diversify into a wider range of feedstock (not just scrap) and to expand further into speciality steels. These technical innovations combined with the relatively low cost and ease of start-up and operation, all helped drive global expansion of mini mills.

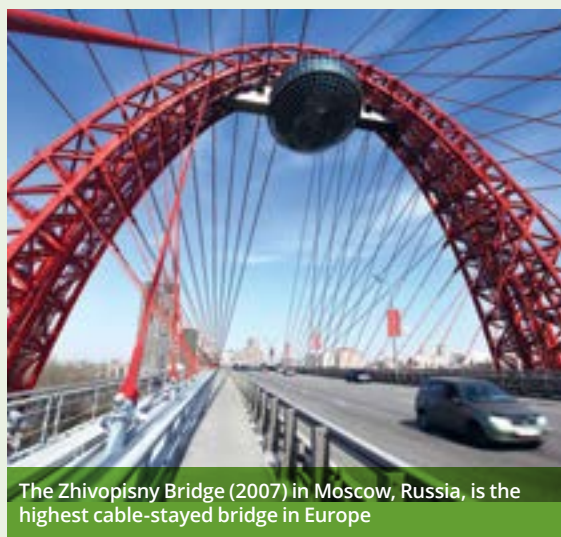
Privatisation brings added growth

At the same time, economic reforms brought new energy to longer established parts of the industry. Many failing nationalised companies benefited from privatisation. Sometimes this led to consolidation, but usually with an injection of capital investment in modernising plants, processes and working practices. Although steelmaking remained mainly a national business, consolidation first started on a regional basis. In 1999 Koninklijke Hoogovens merged with British Steel to form the Anglo-Dutch business Corus and in 2001 Acelaria (Spain), Usinor (France) and Arbed (Luxembourg) merged to form Arcelor in Europe. In Japan, JFE Holdings was formed in 2002 from NKK and Kawasaki Steel.

Russian strength

Despite years of lack of investment, at the time of its dissolution in 1991, the Soviet Union had overtaken Japan to become the world's biggest steel producer. In the 1990s and 2000s, privatisation brought massive investment in new equipment to speed production and reduce costs.

At the same time, the rapidly growing Russian economy of the 2000s coupled with neighbouring China's economic boom created huge demand, providing Russian industry with a vast export market and ensuring its place as a top-five global steel producer.



The Zhivopisny Bridge (2007) in Moscow, Russia, is the highest cable-stayed bridge in Europe



The ArcelorMittal Orbit in Stratford, London, United Kingdom

And then two examples of global consolidation came with ArcelorMittal and Tata Steel of India. Throughout the 1980s and 1990s, the entrepreneur Lakshmi Mittal built Mittal Steel, turning numerous loss-making nationalised companies into profitable private enterprises. Its 2006 merger with Arcelor created ArcelorMittal, the world's largest steel producer at the time, employing more than 260,000 people worldwide. The second instance came in 2007, with the purchase of Corus by Tata Steel.



Number 5 Blast Furnace at the Port Talbot Tata Steel (formerly Corus) Plant in South Wales, United Kingdom

Innovation and global connections

At the start of the 21st century, new technologies are firmly established in the steel industry. Basic oxygen steelmaking (BOS) accounts for some 60% of global production of raw steel. Continuous casting, along with innovations in rolling and finishing, have brought major efficiency gains while reducing the industry's demands on energy for heat and water for cooling.



Piercy Conner's innovation for Indian apartments has made the previously unfeasible solar solution sustainable thanks to steel

Korea's giant POSCO, with its eco-friendly FINEX process that is designed to meet the increasingly strict environmental regulations of the 21st century (with hot-metal quality equivalent to the conventional blast-furnace process) is developing a major new plant, a joint venture in Brazil with Dongkuk Steel and Vale.

Latin American producers, such as Gerdau and Techint, operate mills around the world.

This is to name just a few examples, and new producers are also emerging. In the first decade of the 21st century, Turkey's steel production rose from 15 million tonnes to 29 million tonnes – only outpaced by China and India.



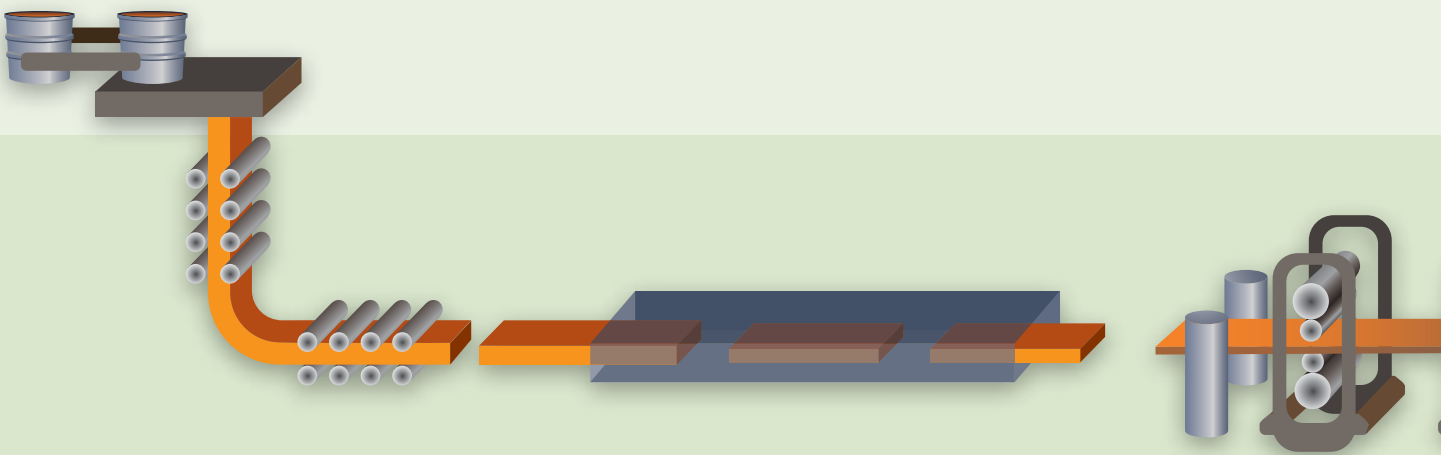
A hot strip mill run-out table



Kağıthane Shopping Mall by Suryapi in Istanbul, Turkey

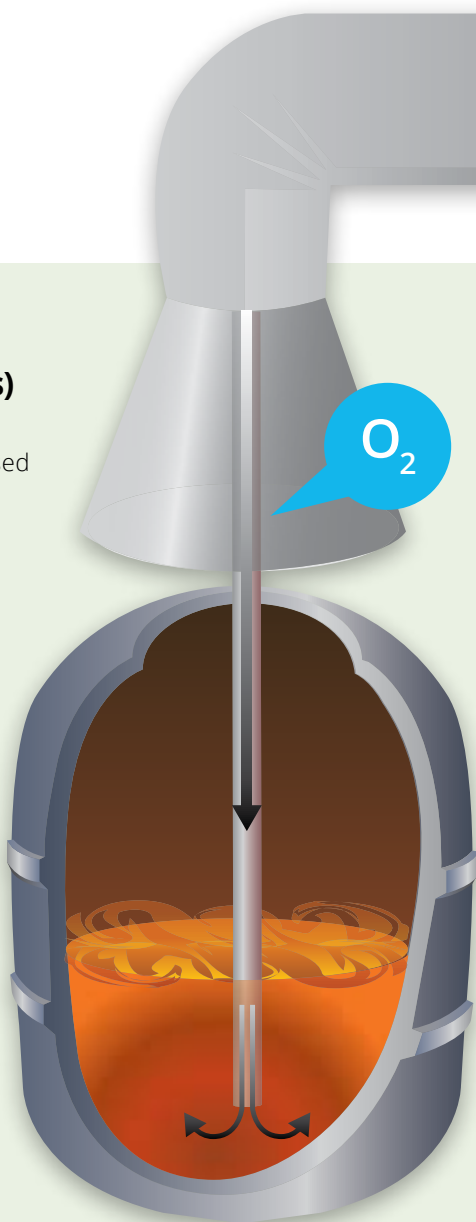
The in-line strip production

In-line strip production (ISP) integrates the thin slab casting phase with the rolling stage. By reducing a liquid strand core, a slab of 15-25mm in thickness may be obtained, with the additional benefits being that there is only a distance of 180 metres from liquid steel to a finished coil and the production cycle lasts no longer than 15 minutes.



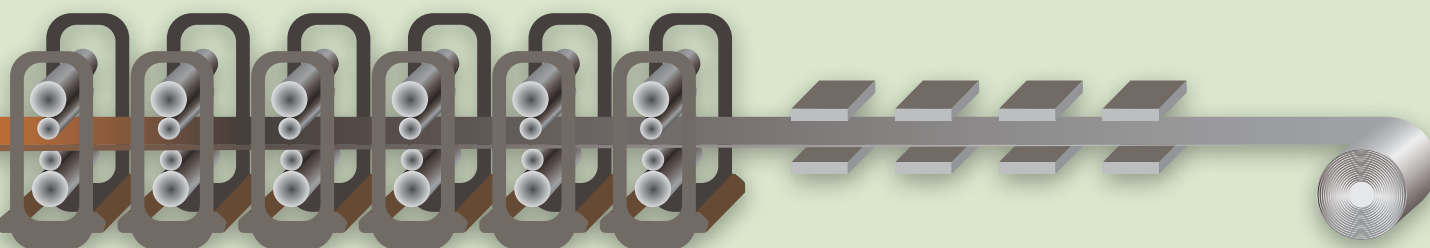
The Linz-Donawitz process (LD process)

The LD process is a method used for refining iron by lowering its carbon content to convert it into steel.



Oxygen is blown into the iron, and carbon as well as the majority of other impurities (such as nitrogen, traces of phosphorus, sulphur and any remaining gangue material) is removed from the iron to convert it to steel that contains less than 1.2% carbon.

If scrap is added, certain contaminants such as zinc, mercury, cadmium, aluminium and plastics are removed as well, and end up in the dust collection system in off-gas or slag, which is tapped before the steel is placed into the ladle for its transfer to the refining station and casting.



Tata: Building on India's steel traditions



India's steel industry owes much to Jamsetji Nusserwanji Tata. In the late 1800s, Tata believed steel could kick-start India's own industrial revolution. While he did not live

to see his dream realised, his prospectors found an ideal location for India's first commercial steel plant at Sakchi, north-east India, which began operations in 1912.

Tata also wanted to create a great city for his workers to enjoy life. Built by his sons, that city – called Jamshedpur in Tata's honour – is now home to more than 1.3 million people, and is among India's richest and cleanest cities. In 2007, Tata Steel acquired Anglo-Dutch manufacturer Corus.



Latam's European connections

One of the BRIC countries, Brazil, is Latin America's largest steel producer. Following the end of its privatisation programme in 1994, many Brazilian producers joined industrial and/or financial groups and, as part of their efforts to improve competitiveness, some steelmakers expanded their activities into logistics-related business, such as seaports and railroads.



Brazilian company Gerdau is the largest producer of **long steel** in the Americas and one of the largest suppliers of special steel in the world. With production facilities in the Americas, Europe and Asia, it was established by German immigrant João Gerda and his son Hugo in 1901. A true

family business, Gerdau has been built on respect for employees and customers. It is also the leading recycler in Latin America, reflecting the importance of environmental responsibility in its ethos.



The Techint group, another giant of Latin American steelmaking, was set up in 1945 by Italian engineer, Agostino Rocca. It was heavily involved in the development of Argentina's industrial infrastructure, including the construction of a 1,600km gas pipeline from Comodoro Rivadavia to Buenos

Aires in 1949. Today, Tenaris – one of the group's companies – is a world leader in the manufacture of seamless steel tubes, mainly for the oil and gas industry. Another group company, Ternium, is a major player in flat and long products in Latin America.



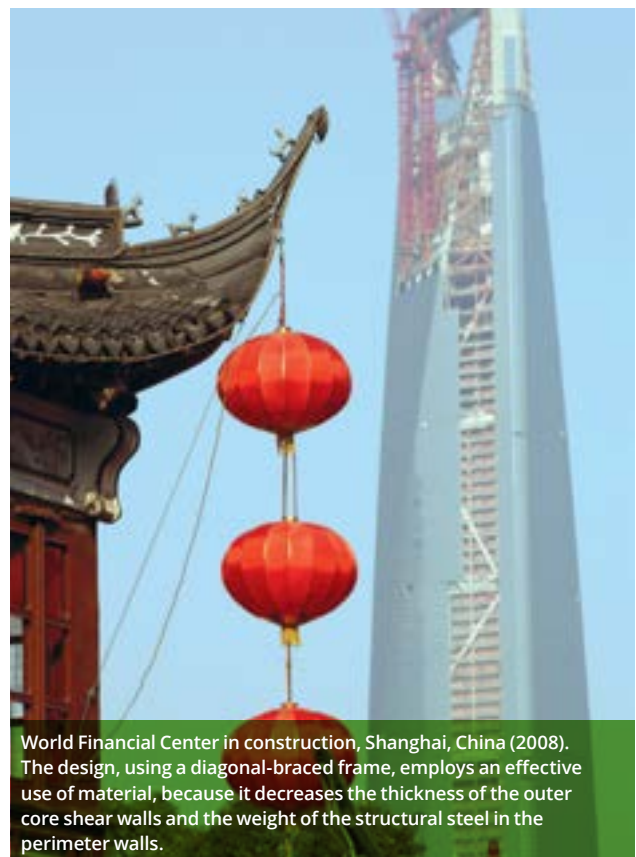
Landscape of the modern city of Beijing, China

The steel dragon

Steel production has always gone hand in hand with economic development. It is a fact much in evidence in China, one of the world's most dynamic economies. Although steelmaking in China – as in India – has ancient roots, the industry was relatively undeveloped until the second half of the 20th century. Following the formation of the People's Republic of China in 1949, the government took steps to develop an industrial infrastructure including new steel plants.

However, the industry only really took off following the economic reforms of the 1980s. These opened up foreign trade, triggering huge economic growth and massive expansion of steelmaking. By the end of 2011, China was by far the world's largest steel producer, with an output of just over 680 million tonnes.

Much of this production goes to support China's rapid urban development. Cities and infrastructure are expanding and being modernised at an incredible rate. In a bid to make the country self-sufficient in steel, the Baoshan Iron and Steel constructed a brand new steel plant at Baoshan near the port of Shanghai in 1978.



World Financial Center in construction, Shanghai, China (2008). The design, using a diagonal-braced frame, employs an effective use of material, because it decreases the thickness of the outer core shear walls and the weight of the structural steel in the perimeter walls.



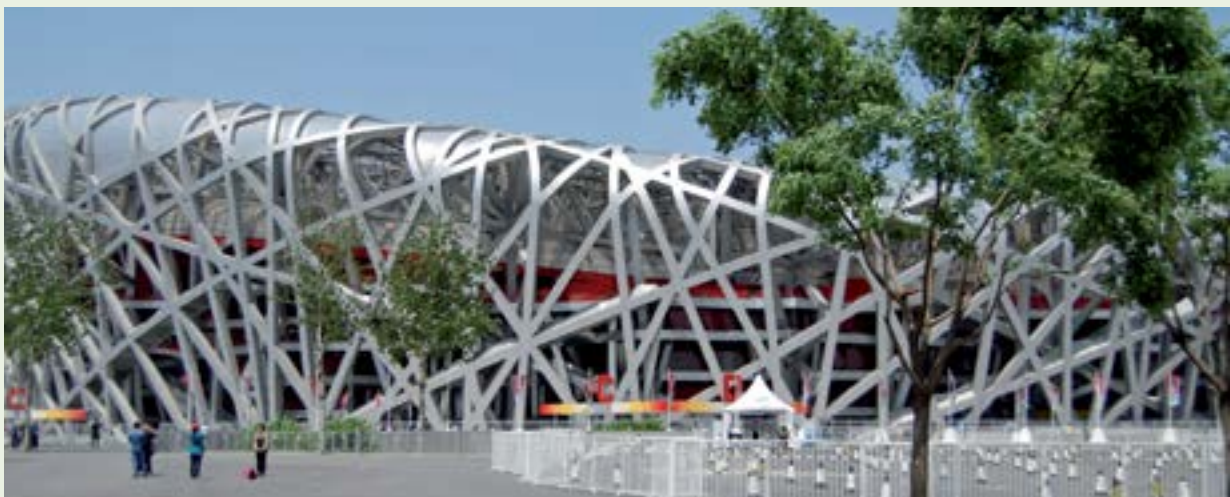
Stainless steel bearings

Many other new plants were also built and by the mid-2000s, there were more than 4,000 steel companies in China producing 350 million tonnes. Yet this was still not enough to meet the demand and China's steel companies have continued to grow.

In 2011, the biggest company was the Hebei Group. It produced more than 44 million tonnes of steel – making it the second largest steel producer in the world. Baoshan Iron and Steel (now known as Baosteel), was close behind with 43 million tonnes, ranking it as the world's third largest steelmaker. The company has some of the industry's most advanced steel plants and specialises in delivering hi-tech steel products for the automotive, household appliance, shipping and oil and gas industries.

Steel for the Games

Shougang (Capital Steel) is one of China's oldest state-owned companies. Its Beijing plant, founded in 1919, was originally built on the outskirts of the city but has since been swallowed up by urban growth. In 2005 as part of a huge drive to rejuvenate the city ahead of the 2008 Olympic Games, the entire plant was re-located 150 km away to a purpose-built island off the coast. The Beijing National Stadium – the so-called Bird's Nest stadium – built for the games used 42,000 tonnes of steel, making it the world's largest steel structure.





Loading of iron ore on an extraction site

An industry on the move

The steel industry has seen its focus shift towards the emerging economies, as these require a huge amount of steel for urbanisation and industrialisation. In 1967, when the World Steel Association first came into being as the International Iron and Steel Institute, the US, western European countries and Japan accounted for 61.9% of world steel production. By 2000, this had been reduced to 43.8%. This trend accelerated in the 2000s, with the rise of China and from 2011 onwards with emerging countries accounting for more than 70% of steel use and production – China now represents around 45%. This shift in momentum looks likely to continue with other developing economies, such as India and countries in Association of Southeast Asian Nations (ASEAN) and Middle East and North Africa (MENA).



Cityscape of Jakarta, Indonesia



Steel industry today and future developments

Sustainable steel

Steel is everywhere in our daily lives from buildings and vehicles to the tin can that conserves food safely for months or years. It is the world's most important engineering material. Nonetheless producing steel is extremely energy intensive. However, once produced, steel can be used again and again. With a global recovery rate of more than 70%, steel is the most recycled material on the planet. What's more, 97% of by-products from steel manufacturing can also be reused. For example, slag from steel plants is often used to make concrete.

Thanks to continuous improvement of steelmaking processes, it now takes 50% less energy to make a tonne of steel than it did thirty years ago. Using less energy means releasing fewer greenhouse gases, a key factor in combating climate change. Indeed, considered over its entire lifecycle, steel products can have less environmental impact than products made from alternative materials such as aluminium or plastic.

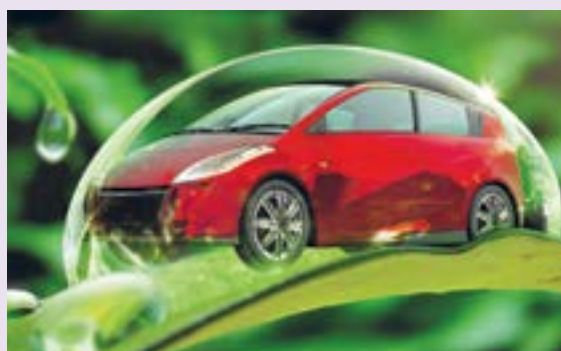
Moreover, today's advanced high-strength steels are stronger and lighter, so less steel is required to deliver the same structural integrity. A lighter car or cargo ship will be more fuel efficient, reducing their greenhouse gas emissions.

Steel also has an important role in the world's growing infrastructure for renewable energy. The latest steels are enabling taller, stronger, lighter-weight towers for wind turbines, increasing their efficiency and reducing the carbon emissions associated with their construction by up to 50%. New roofing systems combine photovoltaic cells with galvanised steel panels. Steel producers are even working with the solar industry to explore innovations such as roofing coated with dyes that can directly generate electricity.

At the same time, steel plants are cleaner and safer than ever before. Improving health and safety is a key industry goal, with manufacturers continually striving to reduce accidents at work. As a result, the industry's lost-time injury frequency rate halved between 2004 and 2009 – the industry is now aiming for an injury-free workplace.

Co-operation on 'greener' cars

A modern car consists of around 50-60% steel. Over the years, steelmakers and the automotive industry have worked closely to make cars stronger, safer and rust resistant. Advanced high-strength steels can reduce lifetime greenhouse gas emissions of a typical five passenger vehicle by 2.2 tonnes. And the industry is working to go further. In the 1990s already, the Ultra Light Steel Auto Body (ULSAB) programme showed ways to achieve weight reduction with a body that fulfils or exceeds performance and crash-resistance at potentially lower cost. A similar programme for electric vehicles, FutureSteelVehicle (FSV), whose results were released in 2011, revealed potential reductions to total life cycle emissions by nearly 70% compared to a current benchmark vehicle. This was achieved through 97% use of High-Strength (HSS) and Advanced High-Strength Steels (AHSS).

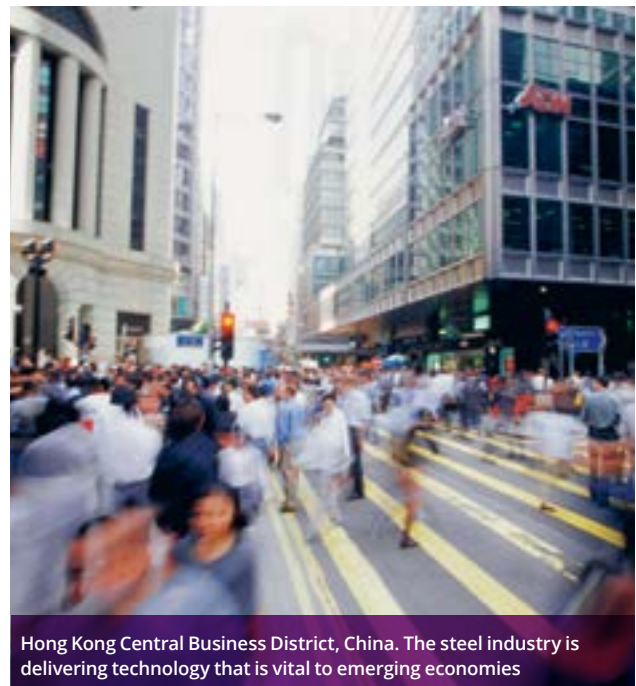


A steel future?

Steel has played a vital enabling role throughout much of human history. It was the material of the highest-priced tools in the Iron Age and the most feared weapons in the Middle Ages. It was the material that drove the Industrial Revolution, and underpinned the economic development of countless countries.

But steel isn't just the material of our past. It will play an equally important role in our future.

The world's population is increasingly urban. In 2010, around half of us lived in towns or cities. By 2050, it will be around 70%. To handle this migration, cities are expanding rapidly to become mega-cities. Building these mega-cities is going to take a lot of materials, not least of which is steel. Housing and construction already consume 50% of all steel produced. As urban population densities increase, so too does the need for steel to build skyscrapers and public transport infrastructure.



Hong Kong Central Business District, China. The steel industry is delivering technology that is vital to emerging economies



Solar power panels, Albuquerque, New Mexico, US. Steel bases are used to ensure the panels' strength and security

The energy needs of emerging countries call for continuing exploration and production of hydrocarbons from conventional and non-conventional sources (shales) and from increasingly demanding environments. The steel industry is delivering the necessary hardware with environment friendly technologies.

Elsewhere, concerns over carbon dioxide emissions, climate change and the availability of fossil fuels are driving the demand for renewable energy sources. Steel is a major material for many of these including solar, tidal and wind power grids, and pipelines for water, gas and resource management.

Innovating together

Steelmakers worldwide continue to improve processes and create new steels for new purposes. Many have their own R&D organisations, but partnership is also a hallmark of steel innovation. For instance, POSCO and Siemens VAI jointly developed the FINEX process, a lower cost, more environmentally friendly alternative to traditional blast furnaces for producing hot metal. The industry-wide FutureSteelVehicle initiative aims to bring more than 20 new grades of lighter weight, cheaper advanced high-strength steels to the market by 2020. There is widespread participation in programmes to reduce CO₂ emissions such as ULCOS in Europe, Course 50 in Japan and the AISI CO₂ Breakthrough Programme in North America. And the industry is increasingly adopting a life cycle approach to increase efficiency, reuse and recycling at every point of a product's life cycle from raw material extraction to recycling of end-products.



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