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The French Brass Industry during the 19th Century

Introduction In circa 1800, innovative processes for producing and working brass revolutionised the manufacture of brass sheets in Europe. This opened up new possibilities for the French brass industry to expand, both by adding value along the manufacturing chain of brass products and by gaining enough expertise to compete successfully on the world markets. The aim of the present paper is to review those processes briefly and to explain how and why the French metallurgical industry took advantage of this technological change.

Brass sheet production before 1800 In the history of copper-zinc alloys (for which "brass" is the generic designation) we can identify two periods when there was a qualitative and quantitative rise in production.[1] The first occurred roughly during the first century BC in Western Europe. The second began some two thousand years later in circa 1800 and lasted a little more than a century. These two periods cut the history of brass into three phases. They are characterised by the way in which zinc was alloyed to copper to producing brass. Evidently, the most straightforward technique is to dissolve metallic zinc (temperature of fusion T_f = 419 °C) in a bath of liquid copper (T_f = 1083 °C), to stir well and to pour the melt into a shaped mould or into the form of a slab for further processing, such as by hammering or rolling. However, this technique was introduced to Europe only in the first decades of the 19th century. The reason for this is that it took a long time to learn to produce metallic zinc on a large scale in a manner that was economically efficient. The basic problems that made production of the metal so difficult were to some extent the high vapour pressure of zinc, but more crucially its high affinity for oxygen. Before 1800 zinc ores, more specifically the oxide ores known generically as calamine, were directly used in a process based on an in-situ reduction of the zinc oxide in the presence of copper. This process will be described below in greater detail.

Brass was well known since the 2nd millennium BC. Indeed, archaeological excavations have even found prehistoric artefacts mainly in the larger region around the Middle East, but also as far as Southwest Asia.[2] Nevertheless, it appears to have been something

1 Jean-Marie Welter: The zinc content of brass: a chronological indicator?, in: *Techne* 18 (2003), pp. 27–36.

2 Christopher P. Thornton: Of brass and bronze in prehistoric Southwest Asia, in: *Metals and Mines. Studies in Archaeometallurgy*, ed. by Susan La Niece, Duncan Hook and Paul Craddock, London 2007, pp. 123–135.

of an exotic material, its most appealing characteristic probably being its yellowish-golden hue. At the end of the first century BC, the Roman Empire experienced a huge increase in the production of brass items made by casting or hammering. It seems that at the beginning of that century, the Celtic tribes in Luxembourg (the Treviri) and Slovenia had more or less simultaneously discovered new, highly productive methods for alloying copper with zinc by using its oxide compounds.[3] Carbonates (smithsonite or zinc spat) and soro-silicates (hemimorphite) are the most representative compounds. The background for this technological push remains unclear. The main reason might have been the discovery of large deposits of calamine in western Germany and northern Italy.[4] It is much easier to handle such ores than the more abundant primary iron-zinc or lead-zinc sulphide ores (zinc blende or sphalerite), which first have to be reduced to zinc oxide. No direct description has survived of the calamine-based process used during the Roman period and subsequent centuries. The first extensive description was written down at the beginning of the 12th century by the monk Theophilus Presbyter in his book *De diversis artibus*.[5] During the following centuries the process did not change fundamentally, with only minor improvements being realised.

The work carried out in recent decades in analysing historical brass artefacts, studying metallurgical treatises, documents and manuscripts (mainly of the 16th and 18th centuries), realising archaeo-metallurgical field experiments[6] and excavating the foundations of furnaces and the remains of foundries has given us a good understanding of the processes involved. In brief, the recipe for making brass consisted of preparing a cement by thoroughly mixing charcoal and finely ground calamine (which may have been roasted beforehand so as to get a purer form of zinc oxide); this cement was then placed into a clay or clay/graphite crucible with small shanks of copper. Hence this is called the cementation or calamine process. Up to twelve crucibles with a typical height of 30 cm were placed on the perforated sole of a cylindrical, open-top furnace. This allowed for a daily production of some 100 kg of brass. The opening in the furnace allowed the crucibles to be inserted and removed easily, and also established a natural draught to fire the charcoal (or coal, which was used increasingly during the modern period). The usual

3 Elisabeth G. Hamilton: *Technology and Social Change in Belgic Gaul: Copper Working at the Titelberg, Luxembourg, 125 B.C.–A.D. 300*, Philadelphia 1996; Janka Istenič and Žiga Šmit: The Beginning of the Use of Brass in Europe with Particular Reference to the Southeastern Alpine Region, in: *Metals and Mines*, pp. 140–147.

4 C. Plinius Secundus: *Naturalis Historiae*, Libri XXXIV, reprint, ed. by Roderich König and Karl Bayer, München/Zürich 1989, p. 12.

5 Ehrhard Brepohl: *Theophilus Presbyter und die mittelalterliche Goldschmiedekunst*, Wien/Köln/Graz 1987, p. 198.

6 For a recent project (2010–2012) see: www.laitonmosan.org.

temperature range for the process was roughly 950–1050 °C. During the heating phase, the residual oxygen present in the crucible reacted with the charcoal to produce carbon monoxide. When the high temperature regime was reached, carbon monoxide reduced the zinc oxide, forming carbon dioxide with the oxygen atoms and liberating zinc as a vapour. Carbon dioxide reacted in turn with the charcoal, leading to a regeneration of carbon monoxide. Part of it was used to restart the reduction cycle, while the excess escaped through the top of the crucible and the furnace opening. Most of the zinc vapour was absorbed into the surface of the copper shanks and diffused into the metal, thereby forming brass. As zinc decreases the melting temperature of copper, liquid layers formed on the surface. The melt dropped down, percolated through the cement and gathered in a liquid pool at the bottom of the crucible. The pools were skipped into convenient moulds to cast ingots for the foundries or thin plates for the hammer mills.

Two questions arise here: what zinc content was achieved, and how pure was the resultant brass? In his description of brass-making in Oker, now a suburb of Goslar, Lazarus Ercker (1528–1594) mentions that the mean content of zinc was 29 %, as determined by weighing the charged copper and the brass obtained.[7] Considering that this value could vary from run to run by a few percentage points, we find that this proportion agrees with the results of analyses of historical objects. These values apply mainly to wrought products such as plates, sheets and wires. It seems that, by trial and error, the metallurgists of the Renaissance had found that brass with 30 % zinc has the best mechanical properties, combining great strength with high ductility. During the Middle Ages the zinc content had been somewhat lower, and after the Renaissance, it increased to slightly above 30 %. For cast products the zinc content was lower, ranging usually between 10 % and 20 %. The purity of the brass was determined by the purity of the ingredients, namely copper and calamine. Relatively pure copper was used for brass making. It was obtained mostly from chalcopyrite-based ores, avoiding *Fahlerz* (grey copper ore) and improving the refining treatment.[8] However, calamine often contained high amounts of lead and iron oxides. During the smelting of brass these were reduced, and the lead and iron atoms were picked up by the percolating brass droplets. By combining calamine ores from different mines, brass makers endeavoured not to exceed a total impurity level of 5 %. The reason for this is that lead and iron – which could make up some 3–4 % and 1–2 % of the brass respectively – form micrometric and sub-micrometric precipitates in brass. When the metal is cold-worked, internal mechanical stresses build up around them,

7 Lazarus Ercker: *Vom Rammelsberge, und dessen Bergwerk, ein kurzer Bericht*, 1565, reprint in: *Lazarus Ercker. Drei Schriften*, ed. by Heinrich Winkelmann and Paul Reinhard Beierlein, Bochum 1968, p. 237.

8 Erich Egg: *Der Tiroler Geschützguß 1400–1600*, Innsbruck 1961, p. 55.

ultimately leading to cracks. These stresses can be reduced by repeated annealing treatments between the working phases, but this means extra fuel costs (id est wood).

The emergence of metallic zinc in Europe Up to the beginning of the 19th century, brass was produced in Europe almost exclusively with the cementation process. This does not mean that metallic zinc was unknown in Europe. The first hints that zinc might be a metal or a semi-metal can be found in the 16th century in the works of alchemists such as Paracelsus (1493–1541). Some small quantities of metallic zinc were actually produced in the Oker plant set up by Ercker to refine lead. Due to its high vapour pressure, the zinc contained in the charge was driven out and condensed on the cold furnace walls as a layer of almost pure metallic zinc. As the walls heated up, the subsequent zinc deposits could react with the residual oxygen in the furnace atmosphere, forming synthetic zinc oxide. This oxide was extensively used for brass making. In around 1600, larger quantities of metallic zinc were imported from India and China, predominantly by Dutch and English trading companies. In both countries, metallurgists had found a way to produce metallic zinc by reducing zinc oxide with charcoal in small vertical clay tubes exposed to a steep temperature gradient. The periods of invention were roughly the 12th century for India and the 15th century for China respectively.[9] The basic reactions are the same as in the calamine process for producing zinc vapour. But contrary to this process, where pieces of copper worked as collectors, the zinc vapour condenses here as a metal in the cold zone of the tube. To avoid overpressure in the tubes, the excess carbon monoxide has to escape through convenient apertures. The difference between the two technologies is that in India the bottom of the tube was kept cold, whereas in China it was the top.

Metallic zinc was not used in Europe to cast zinc artefacts, but only to produce small quantities of brass for special applications such as brazing and jewellery alloys. It is possible that some zinc was added to cementation brass at the end of the 18th century in order to increase the zinc content. We should note that by about 1800 many of the properties of zinc had already been investigated. Even its electrochemical behaviour was known, for Alessandro Volta had already made the first voltaic pile with copper and zinc disks as electrodes. Efforts were also undertaken during the 18th century to copy Asian technology. In Wales, large pots were in use in the middle of the century while small tubes were employed in Carinthia at the end of the century. But both processes were rather inefficient and they were soon abandoned. The breakthrough came in Upper Silesia in 1799, when Johann Christian Ruhberg (1751–1807) began with the horizontal

9 Paul T. Craddock et al.: Zinc in India, in: 2000 *Years of Zinc and Brass*, revised edition, ed. by Paul T. Craddock, London 1998 (Occasional Paper of the British Museum, vol. 50), pp. 27–71; Zhou Weirong: The Origin and Invention of Zinc-smelting Technology in China, in: *Metals and Mines*, pp. 179–188.

positioning of flat-bottomed muffles. Ruhberg carried out his first trials with furnace zinc oxide from the Goslar region. A few years later, Jean-Jacques Daniel Dony (1759–1819) used a similar, but simpler and probably more effective method in his newly built plant of Saint-Leonard in Liège. His calamine ore came from the Moresnet-Kelmis area to the south of Aachen, more specifically from the *Vieille Montagne* (Old Mountain) mine. His basic set-up comprised a stack of long clay tubes – called retorts – with a small cylindrical cross-section. These were filled with a mixture of roasted calamine and charcoal, inserted into a furnace, and heated up to some 1000 °C to allow the reduction reaction to start. Outside the furnace an attachment was fixed to the retort that allowed the zinc vapour to condense while other fumes were retained and the carbon monoxide escaped. The advantage of this was that the tubes could easily be removed when all the zinc oxide was reduced and then be cleaned, refilled and repositioned. Furthermore, the low vapour pressure of ubiquitous ore impurities such as lead, iron, copper et cetera greatly limited their evaporation and led to a metal with a low level of tramp elements. During the 19th century, the purity of zinc was continuously increased by repeated distillation-condensation cycles. Elements with a similarly high vapour pressure, such as cadmium, often became a characteristic trace companion of zinc.

Dony's objective was not so much to produce zinc for making brass, but to manufacture zinc sheets. The Continental Blockade had reduced supplies of copper, so people were looking for alternatives to copper sheets. Dony accordingly equipped his plant with a rolling mill from the start. Fortunately, trials performed during the two previous decades had revealed that by heating zinc up to some 150 °C to 200 °C, the ambient temperature brittleness could be overcome. In this temperature range the metal is sufficiently ductile for sheet rolling and wire drawing. It is worthy of note that one of the first objects made with zinc sheets was a bath tub. Dony offered it to Napoléon to demonstrate that zinc could very well compete with copper (one should not forget that in those days the Austrian Lowlands had been annexed by France). Although the Belgian/Silesian method was a batch process, it was a relatively cheap one and became the standard process for zinc production until the beginning of the 20th century.[10] A craze soon started for these new products, and everywhere in Europe new plants were set up to produce zinc sheets. But disillusionment rapidly set in due to several inherent shortcomings of the material. The excess production capacity led to a crisis in the zinc industry during the 1840s. But activities were soon taken up again: some major deficiencies were eliminated, the demand for cheap sheets for roofing started to grow (mainly in France and northern Germany), the galvanising process had been invented in 1837 by Stanislas Sorel (1803–1871) to protect

10 Eugène Prost: *Métallurgie des métaux autres que le fer*, Paris/Liège [2]1924, p. 1.

steel sheets, and specific alloys for piece-casting were under development. By the end of the century, zinc for brass-making represented only a small fraction of global production. In parallel, the roasting of zinc sulphides into oxides was improved and opened up new possibilities for getting the necessary raw materials.

The production of metallic zinc was extremely beneficial to the European brass industry: first, because zinc was (and is) much cheaper than copper. The copper/zinc price ratio fluctuated during the 19th century between factors of 3 and 4. Thus the price of brass dropped well below that of copper. Secondly, co-melting copper and zinc gave much more flexibility and reliability to the production of copper-zinc alloys with a well-defined zinc content. Furthermore, it allowed manufacturers to increase the zinc content of brass to well above 32–35 %. In 1832, George Frederick Muntz (1794–1857) developed and marketed a brand of brass with 40 % zinc, aimed at fabricating low-cost strips for sheathing wooden ship hulls. Another asset of such a high zinc content – besides its low cost – is that the metal can easily be hot-worked. But it is brittle due to the presence of intermetallic phases, so it is very hard to cold-work the alloy. The bulk of brass production today comprises rods and profiled bars made with this type of alloy for hot forging and free machining. Thirdly, the low level of contaminants in zinc increased the purity of brass, which is very beneficial to cold-working. This evolution is clearly revealed by the major drop in lead and iron impurities that we can observe during the first half of the 19th century, both in wrought and cast brass. Notwithstanding those advantages, it took almost half a century for the brass industry to reorient itself toward the direct co-melting production of brass. As so often, a reluctance to adopt the new technology was first of all a question of mentality.

Sheet production: from hammering to rolling In order to produce brass sheets it is not sufficient to have access to blanks, either plates or slabs. A means of thinning and stretching the metal is also needed. In Antiquity, this was done by hand-hammering. It was only during the so-called Industrial Revolution of the Middle Ages, in the 12th to 13th centuries, that hydraulic energy made possible tremendous gains in productivity by coupling large sledgehammers to waterwheels via camshafts.[11] Water-driven hammers remained the basic tool for producing copper and brass sheets until the end of the 18th century, when they were increasingly replaced by the newly developed rolling mills. Hammers used to shape the sheets into cauldrons, for example, could still be found in the early 20th century when presses started to be introduced. With each stroke, the hammer's head deforms only a small portion of the surface. There is no need for high

11 Jean Gimpel: *La révolution industrielle du Moyen Age*, Paris 1975, p. 9.

power, but the striking frequency has to be rapid to maintain productivity. Up to 300 strokes per minute were customary during the 18th century. To operate such hammers, skilled smiths were needed who knew how to move the plates and sheets rapidly between the hammer's head and the anvil so as to achieve a homogeneous form and thickness.

The principle of the rolling mill was probably known in the Middle Ages. There is evidence that these were used to press and shape strips of ductile materials such as lead. A basic problem – besides casting rollers with low eccentricity and high mechanical strength – is making stands strong enough to keep the rollers in position when the strip enters the gap between them. A wooden construction cannot withstand the separation forces that arise when large surfaces of hard metals are processed. Only large plates of low melting lead ($T_f = 327\,°C$) could be rolled at the beginning of the 18th century because the metal recrystallises dynamically during rolling. Stands built with steel bars enabled narrow strips of silver and copper to be rolled that could then be stamped into coins. Rolling copper, and brass too, soon afterwards, was only developed properly at the end of the 18th century. One reason for this was the Royal Navy's demand for large numbers of sheets to sheath the wooden hulls of their men-of-war and protect them from shipworms and weed, while another was that metallurgists had meanwhile learned to produce large, high-quality elements in cast iron such as rollers and stands. Over the course of several decades, rolling mills were generally adopted. They led to greater productivity, better quality and safer working conditions, and could be operated with lesser-skilled workmen.

The beginning of brass production in France by co-melting copper and zinc The Restoration period in France, after the fall of the First Empire in 1815, saw a revolutionary shift in its brass industry. Brass was now produced in France for the first time, and was done by going directly to co-melting copper and zinc. The problem faced by France, both in the past and even today, is that it lacks notable deposits of metallic ores. This holds first of all for copper and zinc. Even if small-scale mines were sometimes in operation, most copper had to be imported. But instead of importing ores for further processing, French craftsmen during the Ancien Régime purchased sheets and foundry ingots directly from Germany, Sweden, England and Japan. They did the same with brass. During the 18th century, brass was mainly imported from the Meuse valley in the Austrian Lowlands and from the Aachen/Stolberg area in Germany, but also from England and increasingly from Sweden. Thus France lacked any experience of making brass with the cementation process. Copper and brass semi-products were shaped into final products in various places in the French provinces that are still known today for having had a high concentration of metalworking craft shops, such as the following towns that are known for manufacturing objects for daily use with metal sheets and wires: Villedieu-les-Poêles and

L'Aigle in Normandy, the Rouergue in south-eastern France, and Lyon and its surroundings.[12] The craftsmen in Paris were mainly specialised in making luxury goods.

The first plants in France that were installed to produce copper sheets were set up at the end of the 18th century. The driving force behind this was the French Navy's demand for metal sheets to sheath their ships. The French had experienced the superiority of the British copper-sheathed ships during the American War of Independence (1775–1783) and wanted to be able to match them. New plants were built whose layout and equipment were largely inspired by English plants.[13] A little industrial espionage also helped to get the necessary information. A start was made in 1781 by Michel Louis Lecamus de Limarre, who came up with the idea of producing sheets in France and of no longer relying on imports. Operations began the following year in Romilly-sur-Andelle, a village located 20 km upward of Rouen on the Seine. The real start was in 1785 when new, financially powerful associates joined the company.[14] In that same year, Antoine Frerejean (1736–1789) and his sons installed rolling capacity in their copper plant in Pont-Évêque, a suburb of Vienne.[15] Two years later, Antoine-Laurent Jaquier de Rosée began to produce copper sheets in Landrichamps next to Givet. It is worthwhile noting that these plants were innovative in that they produced sheets mainly by rolling and only to a lesser extent by hammering. Hydraulic energy continued to drive the mills, the hammers and the bellows of the annealing furnaces. Some twenty years later, further rolling mills were established: in 1806 in Fromelennes, a suburb of Givet, by Gédéon de Contamine (1764–1832), in 1807 in Dillingen (the Sarre was part of France at that time), and in 1809 in Niederbruck north of Masevaux.[16] Although most of the production was for the navy and more and more for civilian ships, the plants rapidly diversified their production, both in terms of markets and alloys. Contamine used the proximity to the *Vieille Montagne* to import calamine to produce brass. He also started rolling brass in 1810 with the help of an English workman. He could reportedly produce brass sheets with a thickness of ⅓ mm for making wind instruments – "products difficult to manufacture".[17] There was no problem for the plants

12 Yvon Alauzet et al.: *Cuivres en Rouergue*, Rodez 1996 (Guide des mœurs et coutumes, vol. 8).

13 Anne-Françoise Garçon: *Mine et Métal – 1780–1880. Les Non-Ferreux et l'Industrialisation*, Rennes 1998, p. 37.

14 Alexandre Louis Nicolas Roëttiers de Montaleau: *Notice historique sur l'établissement des fonderies de Romilly-sur-Andelle*, Paris 1850, p. 4.

15 Alain Frerejean and Emmanuel Haymann: *Les maîtres de forges*, Paris 1996, p. 107.

16 Hermann van Hamm: *Beiträge zur Geschichte der Aktiengesellschaft der Dillinger Hütte*, Koblenz 1935, p. 97; Joseph Scheubel: *La cuivrerie de Niederbruck et la Haute Vallée de Masevaux au XIXème et au XXème siècle*, Strasbourg 1971 (Recherches et Documents, vol. 11), p. 7.

17 François Pierre Nicolas Gillet-Laumont: Rapport sur les Cuivres laminés, et sur les feuilles de Zinc fabriquées par M. Gédéon de Contamine, in: *Bulletin de la Société d'Encouragement pour l'Industrie Nationale* 9 (1810), pp. 245–247.

in getting brass ingots for the mills because the Meuse valley and the left bank of the Rhine now belonged to France.

As soon as Dony started to roll zinc sheets in Liège, Contamine acquired some specimens and sent them together with copper and brass sheets to the *Conservatoire des Arts et Métiers* in Paris for evaluation. At the same time, the directors of Romilly perceived the new material as a threat to copper sheets and in 1810 wrote a report emphasising the shortcomings of zinc.[18]

During the next five years nothing happened. The situation changed after the Congress of Vienna, when France had to give up the northern countries she had annexed during the Empire. This meant a loss of markets both for a cheap supply of brass as well as for the easy sale of copper goods. Thus the copper work of Dillingen, which produced sheets for the French Navy, was moved with all its rolling mills to Imphy, upstream of Nevers on the Loire.[19] Imphy became an important manufacturing site of copper and brass sheets, but shifted to steel during the middle of the century. A similar evolution took place at the Frerejean plant. Meanwhile, two companies decided to produce brass using the new co-melting technology. The first was the plant of Romilly. Following a suggestion from one of its directors, Alexandre Louis Nicolas Roëttiers (1778–1855), trials to produce brass sheets started in 1814. Their main difficulty was to obtain surfaces free of spangles. Eventually, sheets without surface defects were able to be made, and in 1816 a new shop was set up dedicated to their products. It was followed by the wire-drawing plant of the Mouchel family in Boisthorel near L'Aigle. The mill there had started to draw steel wires in the middle of the 17th century. It was acquired by Jean-Baptiste Mouchel (1723–1789), the inventor of the first mechanical coiler, at some point between 1765 and 1770. It was his grandson, Pierre-Jean-Baptiste-Felix Mouchel (1786–1871), who began to draw brass wires in 1807. In the years thereafter he invented the first modern gauge based on geometric progression, in order to standardise the diameter of the wires. In 1820, under pressure from the decline in the steel business, Mouchel transformed his plant into a brass wire drawing mill. To avoid having to import brass blanks he set up his own technology with the help of the chemist Jean-Antoine Chaptal (1756–1832). For co-melting copper and zinc he developed oblong, slightly barrelled crucibles. These were placed into a specially designed furnace fired with coal and a natural draught (four potager).[20] After a few years of trials, he obtained good results and in 1824 installed a brass foundry and rolling mill. The Boisthorel plant, which today belongs to the KME Group, is the most

18 Gorlay, Malus and Roëttiers: *Réponse au mémoire sur le zinc malléable*, Paris 1810.

19 Anon.: *La Société de Commentry-Fourchambault et Decazeville 1854–1954*, Paris 1954, p. 60.

20 Albert Bounaix: *Histoire de l'usine de Boisthorel*, L'Aigle 1967, p. 20.

important copper mill in France that specialises in brass rods and wires. The other plants in Givet, Imphy, Niederbruck followed the trend to go directly to metallic zinc as a raw material. Because of its higher density and zinc content, transportation costs for brass were lower for the metal than for the calamine. New plants were also set up, mainly in north-western France. This industrial development was made possible to some extent because the old established brass industries in Germany, England, Sweden and Belgium et cetera no longer had a competitive advantage. During the first half of the 19th century, they had also had to convert to the new brass manufacturing and rolling technologies. This does not mean that no cementation brass was imported during this period, but the quantities involved diminished. France now actually started to export brass, and its sheets were highly appreciated on the foreign markets. Furthermore, the existence of the upward process chain simplified the recycling of old brass objects. For this reason it took some time in France before the maximum level of impurities in brass sheets was significantly reduced.[21]

How were brass sheets made during the 19th century? There was no specific French technology, even though French engineers achieved improvements in certain aspects of the process, thereby leading to the overall excellent reputation of French brass. Various documents, mainly related to the practice in Romilly, can give us a clear idea of the different steps of the process, which remained more or less unchanged during the whole century.[22] It was only during the period 1900–1930 that innovations led to today's technology. Copper was melted in crucibles similar to those of Boisthorel prior to the addition of zinc ingots. To avoid the inhalation of the zinc fumes, the foundrymen had to clench their ties between their teeth. The melt was cast into moulds made of white cast iron that could be opened like a briefcase. Typical dimensions were 84×36 cm. The thickness of the plates reached 2 cm by the end of the 19th century. These plates were cold-rolled, first in a breakdown mill, then in a finishing mill. Because the diameters of the rolls were rather large and the mills were low in power (being driven mostly by waterwheels until the end of the century, when electric motors began to take over), only soft metals could be rolled. Thus many intermediate heat treatments were necessary to remove the hardness introduced by cold-working and to restore the initial soft microstructure of the metal. Meanwhile, furnaces had been adapted to use combustion gases to limit oxidation. At the beginning of the 20th century, the hydraulic power available was of the order of 10 hp. Successive improvements of the waterwheels, due to experimental results, led to a power of up to 50 hp. Flywheels were also used to store energy that could

21 See the article by Marianne Senn et al., pp. 398–419.

22 Jacques Buchetti: *La Fonderie de Cuivre Actuelle*, Paris 1905.

then be released during the rolling phase. The weakness of the mills made it almost impossible to obtain thin gauge strips. This led to the so-called doubling technique. The sheets were folded and rolled. When the desired thickness was attained after several cycles, the individual strips were then peeled off. Fortunately, the large scale production of sulphuric acid had begun at the beginning of the century, which meant that the sheets could be pickled so as to remove the oxidised surface layer and it was no longer necessary to shave the surface as had been the normal practice in previous centuries.

The French recycled brass scrap, but otherwise continued to import the copper and zinc from all over the world that they needed for brass making. Until 1820, most of their copper came from Sweden and Norway. As the mines there were exhausted, copper was imported until the middle of the century from Russia, the Near East and England. Then Peru, Chile, Spain, Australia and – increasingly – the USA provided copper. Often, copper was purchased as black copper, so many French plants installed refineries to further purify the metal. The level of residual impurities for sheet material was usually less than 0.5 %.[23] Zinc came mainly from Silesia and Belgium (zinc from the *Vieille Montagne* was considered to be the purest) and from 1870 onwards for several decades a small amount of it came from central France. Although the raw materials were imported, many of the semi-finished products and manufactured goods were exported, with much success.

Brass sheets had to serve two large markets. The first was transportation. The protection of the wooden hulls of ships was now a commonplace. Brass was the preferred material for this on account of its good corrosion resistance and low price. As forming the brass was not so demanding, higher zinc concentrations of between 33 and 40 % were desired. Brass was also used to manufacture tubes, usually by brazing, exempli gratia for the emerging locomotive market. The other major market was for vessels of all kinds – from large cauldrons for the food and beverage industry to small household pots. Here, brass's good forming properties were a further advantage. Speciality markets for brass were music instruments and tableware.[24] Two innovations that had a major, positive impact on this market should be mentioned. The electrolytic silver plating of brass was begun in the years 1853–1856 by the jewellery and tableware manufacturer Charles Christofle (1805–1863) thanks to his having acquired the patents of George Richards Elkington (1801–1865).[25] A further possibility for whitening brass was to add some 10 % of nickel – an alloy called *maillechort* in France in honour of Maillet and Chorier, who developed the alloy in 1819 in Lyon.

23 Jean-Marie Welter: La couverture en cuivre en France. Une promenade à travers les siècles, in: *Monumental* 2 (2007), pp. 104–112, here p. 104.

24 See the article by Cyrille Grenot, pp. 11–102.

25 Marc de Ferrière le Vayer: Christofle. *Deux siècles d'aventure industrielle 1793–1993*, Paris 1995, p. 62.

From 1871 to 1914 and beyond: new markets and new technologies The French brass mills did not suffer very much during the 1870/71 war when German troops invaded northern France. They were able to resume the production of copper and brass goods very quickly and thus avoided making massive imports of brass goods – although they had to import raw material as mentioned before. Furthermore, the reconstruction of the army and navy, plus the concurrent introduction of modern breech-loaded firearms, opened up new opportunities for brass sheets. The demand for sheets of CuZn30 (so-called cartridge brass) increased considerably because of its outstanding deep-drawing properties.

Many brass mills became part of the military-industrial complex of the Third Republic. Pierre-Eugène Secrétan (1836–1899) is the best known of the industrialists involved. In 1880 he became the general manager of the *Société Industrielle et Commerciale des Métaux* (SICM), the most important manufacturer of copper and copper alloys semis, not only in France, but across the world. He achieved this at the time of the Long Depression during the last quarter of the century. Secrétan's interest in the copper business started when he came as a young man to Paris – without any formal higher education. He rapidly acquired enough money to purchase the copper and brass mill Saint-Victor in the village of Sérifontaine in 1869. This village is situated halfway between Paris and Dieppe, thus some 60 miles northwest of Paris on the historical river Epte. The mill was a typical example of the plants set up in France at the beginning of the century to process zinc and to produce zinc and brass sheets. It was the only one of a complex of small mills to survive that had been established by Baron Charles Marie Alexandre d'Arlincourt (1787–1864) and his family in 1833/1835 along the Epte, taking advantage of its hydraulic energy. The depression of the zinc market some ten years later had led to the bankruptcy of the Arlincourt group. Saint-Victor was able to continue working as a copper and brass rolling mill under various owners until it was acquired by Secrétan in 1861. This plant was finally closed just a few years ago, by which time it belonged to the KME group. One of the plant's specialties was the production of *laiton à musique* (music brass) for making musical instruments. This brass product is characterised by a very small scatter of mechanical and micro-structural properties. It is also noteworthy that the 80 tons of copper sheets that Secrétan gave to Bartholdi for the construction of the Statue of Liberty were rolled in Sérifontaine.[26]

In 1873, the French government contacted Secrétan with a proposal for him to build a new brass mill for the production of cartridge brass. One criterion for the location of the plant was that it should be far away from the German border. Castelsarrasin was then chosen, a small town situated in south-east France on the Dordogne, some 40 miles north of Toulouse. The place was perfect, being in a region with a long tradition of making

26 Jean-Marie Welter: Understanding the Copper of the Statue of Liberty, in: JOM (May 2006), pp. 30–33.

copper products, with easy access by railroad and river ships and not far from the ammunition factory of Tarbes. This plant, named Sainte-Marguerite after Secrétan's elder daughter, began operating in 1875/76. During the years 1886–1888, Secrétan continued to expand his activities. He acquired the abovementioned plant of Givet in 1878, which is still in activity as a tube mill of the KME Group. In 1881 he merged his plants with those of the Laveissière family and together with them formed the SICM. Further smaller acquisitions were made during the ensuing years. At the end of the decade the SICM produced some 35,000 tons of copper semi-products per year, amounting to 10 % of the total world production.

Given this immense production – a large part of which went into armaments as *laitons de guerre* (war brass) – Secrétan faced the fundamental French problem of the absence of mining resources for copper and, to a lesser extent, for zinc.[27] He had to secure the supplies of raw materials for his plants. The general political context and the experience of the Franco-Prussian War had shown that it was wise to short-circuit British and German copper supplies. So in 1887 he entered into an agreement with American copper mining companies such as Anaconda and Calumet and Hecla, and with Spanish companies such as Rio Tinto (though this was controlled by British capital) to set up a copper syndicate. He offered to purchase all the copper produced at a stable price. This was calculated as the mean of the price asked for copper during the previous decades, which was somewhat higher than the 1887 price fixed by the recently created London Metal Exchange (LME). This attempt to corner the market failed because Secrétan, his French associates and their firm's bank did not have sufficient financial resources to buy all the copper offered to them from both mining and recycling. As a result, the SICM and its bank, the Comptoir d'Escompte de Paris (the forerunner of the Banque Nationale de Paris, now BNP Paribas), went bankrupt in 1889 and Secrétan had to sell off his art collection to pay off his debts. However, none of this stopped him from continuing to work as a copper businessman until his death in 1899. In 1891 he established a new plant in Dives on the English Channel to exploit and improve the patent of the Elmore brothers for manufacturing large copper tubes by means of electro-deposition.[28]

In 1893 a new company, the Compagnie Française des Métaux (CFM), was incorporated with the goal of taking over the plants of the SICM. Under the leadership of Georges Vésier (1858–1938), the CFM became one of the finest manufacturers of copper and copper alloys. Other companies did well too, demonstrating the strength of the French brass industry at the end of the 19th century. One aspect that must be mentioned once more is

27 Maurice Altmayer and Léon Guillet: *Métallurgie du Cuivre et Alliages de Cuivre*, Paris 1925, p. 18.

28 Eric Ratzel: Un aventurier des temps industriels. Pierre Eugène Secrétan (1836–1899), in: *Cahiers d'Histoire de l'Aluminium* 22 (1998), pp. 37–48.

the French industry's search for foreign markets and how it set up sales points all over the world. There were also less pleasing occurrences, such as the closure of the Romilly plant in 1898, which had been one of the pioneers in the introduction to France of brass-making by the co-melting process a century before.

At the end of the 19th century and at the beginning of the 20th, new developments in technology arose that served to complete and amplify those made in around 1800.[29] It will suffice for our purposes to mention them briefly here:

- the high-temperature extrusion press was invented by Alexander Dick in 1894 for the production of high zinc brass rods, tubes, profiles and wires;[30]
- the electrolytic refining of copper and zinc was developed in around 1900 and allowed sheet brass to be manufactured to a yet higher degree of purity;
- channel and crucible furnaces were developed in the late 1910s by the companies Ajax-Wyatt and Russ that were heated by means of electrical induction;
- high-speed multi-cylinder rolling mills with decoilers and coilers were developed between 1900 and 1920, as were hot-rolling mills;[31]
- continuous casting with an oscillating open mould of brass rods and slabs was invented by Siegfried Junghans (1887–1954) in 1933, allowing for a tremendous increase in weight.[32]

The French plants rapidly mastered these new technologies, and the French brass industry grew into one of the finest in the world by the middle of the 20th century; it was only some 30 years ago that the industry dwindled away.

Conclusion As we have seen above, French industrialists in about 1800 were astute enough to seize the opportunities offered by technological change and so entered the field of copper and brass manufacture, despite having had no previous experience. But we cannot overlook the fact that their efforts were to a large extent initiated and supported by the international political context and by France's desire to have a strong army and navy.

29 Jean-Marie Welter: Du laminage à la coulée continue. Le regard de l'industriel, in: *Quatre mille ans d'histoire du cuivre*, ed. by Michel Pernot, Bordeaux 2016.

30 Martin Bauser: Historic Development of Extrusion, in: *Extrusion*, ed. by Martin Bauser, Günther Sauer and Klaus Siegert, Materials Park ²2006, p. 2.

31 Carl Schmöle: *Von den Metallen und ihrer Geschichte*, vol. 1, Menden 1969, p. 177.

32 Ehrhard Hermann: *Handbuch des Stranggießens*, Düsseldorf 1958, p. 605.

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