COLD ROLLING OF STEEL
MANUFACTURING ENGINEERING
AND MATERIALS PROCESSING

A Series of Reference Books and Textbooks

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2. Cold Rolling of Steel, William L. Roberts

OTHER VOLUMES IN PREPARATION.
COLD ROLLING OF STEEL

William L. Roberts
Preface

Although greater tonnages of metals are processed by rolling than by any other metalworking technique, relatively few books have been written on this method of deformation. Most of the treatises that have appeared on the subject are out of print, are difficult to obtain, and, of course, do not reflect the contemporary state of the art in rolling technology. Moreover, authors have generally felt impelled to discuss the subject in the broadest terms, thereby treating both the hot and cold rolling of ferrous and nonferrous metals. Naturally this extensive scope limits the depth to which the subject may be examined and, as a consequence, it is unusual to find any references to such topics as roll cooling, rolling lubrication, and shape of the rolled product.

Accordingly, it was my belief that a current book on rolling should be written but that its contents should be examined in as great detail as possible. This book was therefore written with the intent of providing the metalworking student, the mill builder, the rolling mill operator, the user of cold-rolled products, and, indeed, anyone who has an interest in the subject, with as much information as possible on the technology.

As will be noted, the book is basically a synopsis of information published in the technical literature, organized in such a manner as to acquaint the reader with the history of cold rolling, the equipment currently in use, the behavior of the rolling lubricant, the thermal and metallurgical aspects of the subject, mathematical models relating to rolling force and power requirements, the subject of strip shape, and the further processing of cold-rolled steel. For those readers wishing to pursue the subject in even greater detail, copious references are conveniently given as footnotes on the relevant pages.

In manuscript form, this book has been used in teaching courses in cold rolling and rolling lubrication in both the United States and Mexico. In its published form, it is hoped that it will find much more extensive use, not only as a textbook, but also as a reference book and bibliography on cold-rolling technology.

William L. Roberts
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Chapter I  The History of Rolling

1-1 The Early History of Rolling

In its earliest beginnings, the rolling of flat materials was undoubtedly limited to those metals of sufficient ductility to be worked cold, and it is probable that it was first performed by goldsmiths or those manufacturing jewelry or works of art. Yet, as is the case with many other important processes, metal rolling cannot be traced to a single inventor.

During the fourteenth century, small hand-driven rolls about half an inch in diameter were used to flatten gold and silver and perhaps lead. However, the first true rolling mills of which any record exists were designed by Leonardo da Vinci in 1480. (See Figures 1-1 and 1-2.) Sketches in his notebook show two mills, driven by worm gears, for rolling lead sheets and also a machine for producing tapered lead bars by means of a die and a spiral roll. Yet, there is no evidence that these mills were ever built, and there is a fair degree of certainty that metal rolling was not of any importance before the middle of the sixteenth century.

Before the end of the sixteenth century, however, at least two mills embodying the basic ideas of rolling are known to have been in operation. A Frenchman named Brulier in 1553 rolled sheets of gold and silver to obtain uniform thickness for making coins and mills for rolling mint flats were in use in 1581 at the Pope’s mint, in 1587 in Spain, and in 1599 in Florence. In 1578, Bevis Bulmer received a patent for the operation of a slitting mill which consisted of a series of discs mounted on two spindles, one above the other, in such a manner that the flat bar passing between the revolving discs was cut into strip. A mill of this type was set up at Dartford, in Kent, in 1590, by Godefroi de Bochs, a native of Liege, Belgium.

During the same period, lead was also beginning to find increasing use for roofing, for flashing, for the fabrication of gutters, and for other purposes. Salomon de Caus of France, in 1615,

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built a hand-operated mill for rolling sheets of lead and tin used in making organ pipes, the rolls being turned by a "strong-armed cross" attached to the lower axle as illustrated in Figure 1-3.

Figure 1-2:

Figure 1-3:
Mill Built by Salamon of Caus to Roll Sheets of Lead.

With the exception of the Bulmer slitting mill, mentioned above, all of these early developments pertain to the rolling of the softer metals, presumably at ambient temperatures. Johannsen, in "Geschichte des Eisens" says, "The use of rolls in an iron works was a German development of the 16th century. Belgium and England both started to use rolls about the same time, and they are both sometimes cited as the birthplace of rolling." All three nations probably reached this development at about the same time, but there is little evidence of anything other than slitting mills in the 16th century, and still less evidence to give any nation a clear claim to priority. Such information as is available indicates that, in the rolling of iron, Great Britain led the way. No record of developments during the first half of the 17th century exists, but we know that in 1665 a rolling mill was in operation in the Parish of Bitton, near Bristol, and it is stated that, from 1666 on, iron was rolled into thin flats for slitting.

The rolling of bars was foreshadowed during this period but was not brought to fruition. In 1679 a patent was issued covering the finishing of bolts by rolling, and in 1680 bars were being passed through plane-surfaced rolls to flatten out irregularities. A pamphlet on the "British Iron Trade" published in 1725 states, however, that even at that date all bars were hammered.

However, by 1682, large rolling mills for the hot rolling of ferrous materials were in operation at Swalwell and Winlaton, near Newcastle, England. Using these mills, bars were rolled into sheets and the sheets cut into rods at the slitting mills. Soon after this date, at Pontypool in Wales, John Hanbury began using at his ironworks a rolling mill as an independent machine for the production of thin sheet iron. Edward Llwyd, in a letter dated June 15, 1697 wrote, "One Major Hanbury of this Pontypool shew'd us an excellent invention of his own, for driving hot iron (by the help of a rolling machine mov'd by water) into as thin plates as tin . . . They cut their common iron bars into pieces of about 2 ft. long, and heating them glowing hot, place them betwixt these iron

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rollers, not across, but their ends lying the same way as the ends of the rollers. The rollers, moved with water, drive out these bars to such thin plates, that their breadth, which was about 4 in., becomes their length, being extended to about 4 foot, and what was before the length of the bars is now the breadth of the plate.”

Although Major Hanbury designed the rolling mill described in the letter and illustrated in Figure 1-4, there is no evidence that he originated the idea of hot-rolling bars into thin sheets since it is believed that the practice was general throughout Europe by 1660 being known in Germany very early in the century. At any rate, Germany monopolized the growing English market for tinplate from shortly after 1620 until Major Hanbury began tinplate manufacture in this same Pontypool works sometime before 1720. After that, for more than 150 years, Wales was the major source of tinplate and terne plate.

During the early part of the eighteenth century, there is no doubt that rolling mills were in common use both in England and on the continent. Christopher Polhem (1720 — 1746), Sweden’s great mechanical genius, wrote of rolling mills at about this time and his writing indicates that he assumed his readers were familiar with them. Polhem himself designed a mill very similar to the modern Lauth mill, except that his mill utilized four rolls, with the backup rolls driven.

A “machine for rolling sheets of lead”, that really foretold the shape of subsequent rolling mills, was brought to France from England in 1728. This mill, shown in Figure 1-5, used rolls five feet long and twelve inches in diameter and was equipped with a roller table 24 feet long at front and back. It was a radical departure from the accepted mill design of the day, being a reversing mill, controlled by a clutch and gearing system. The plain rolls could be replaced with other, grooved rolls sixteen inches in diameter, with grooves ranging from four to two inches in diameter, with which hollow cast lead ingots were rolled into pipe over a mandrel.

In 1728, a patent for a mill to roll hammered bars “into such shapes and forms as shall be required” was issued to John Payne in England. However, Payne’s concepts (shown in Figure 1-6) do not appear to have been reduced to practice, but the rolling of iron bars and shapes was of interest to steelmakers and appears to have been practiced. For example, in 1747, the Academie des Sciences appointed a commission to visit a new mill at Essonne, France, which rolled iron bars. By this time, the practice of polishing iron plates for tinning by cold rolling was also in vogue. In 1759, a patent was granted to Thomas Blockley of England for “polishing and rolling metals” — a

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Figure 1-5:
Rolling mill built in England and shipped to France in the early eighteenth century. (Illustration from "Machines Approvees par l'Academie des Sciences", Published in 1728.)

Figure 1-6:
Rolls designed by John Payne in 1728 to produce round bars. (Illustration from "Machines Approvees par l'Academie des Sciences". Edition published in Paris in 1728.)

Figure 1-7:
English patent issued to John Purnell in 1766 for grooved mills driven in unison by coupling boxes and nut pinions. (Staffordshire Iron and Steel Institute Proceedings.)
broad description which really boiled down to rolls which the user could groove to suit his requirements; and in 1766, another Englishman, John Purnell received a patent for grooved rolls with coupling boxes and nut pinions for turning the rolls in unison. (See Figure 1-7.) Until this time, rolls were individually driven, and the unequal rates of revolution caused excessive roll wear, as well as making it necessary to install guides on both sides of each roll.

In this same period, the general appearance of these hot mills was beginning to change to the modern form. For example, the cast housing and the single screw each side of the mill were featured in English patent specifications filed by William Playfield in 1783.† (See Figure 1-8.)

Figure 1-8: English patent specifications filed by William Playfield in 1783. (Staffordshire Iron and Steel Institute of Proceedings.)

In the manufacture of hand-forged plates for tinplating, it had been the practice to hammer several layers of metal at one time. Accordingly, when the rolling mill came into use for producing sheets for tinning, it became the practice, about 1756, to double the sheet after some elongation and then proceed with the further rolling of the two thicknesses of metal. Sometimes in this “pack rolling” or “ply rolling” the doubling was repeated so that four thicknesses of steel were rolled simultaneously.

The aforementioned hot-rolling mills consisted essentially of a single-stand of two rolls, one above the other. As described by Shannon,* “the operating principle of this type of hot mill consists briefly of the following steps: heat the piece, pass the piece through the rolls, push the piece back over the top roll with hand tongs, pass the piece through the rolls again, and so on until the piece being rolled either is of the required thickness or else has cooled down to the point where it must be reheated before the rolling can continue. This is only a bare outline of the elements of the operation, which is very much further complicated by matching (putting two or more sheets together), doubling the pack, adjustments of the rolls, and various other factors, according to the nature of the sheets being rolled. Owing to the fact that the piece is fed to the rolls by the roller, passes through the rolls, is caught on the other side and handed back to the roller for passing through the rolls again, and since there are only two rolls, one above the other in the set, this conventional sheet hot mill or sheet mill is described as a “two-high, pull-over mill”. More than one of these mills may be employed in the rolling unit, each performing a separate stage of the work, but the principle of each remains the same.”

The eighteenth century also saw the advent of the tandem mill in which the metal is rolled in successive stands. The first true tandem mill of which we have record was patented in England by Richard Ford, in 1766, for the hot-rolling of wire rods. James Cockshutt and Richard Crawshay, about 1790, erected a four-high tandem mill near Sheffield, England. This mill was about five feet in length and less than two feet high, with a capacity of, probably, one or two tons per day. A later patent, issued in 1798, refers to a tandem mill for the rolling of plates and sheets. In the same year, John Hazeldine added mechanical guides to a rod mill, as shown in Figure 1-9.

1-2 Later Developments in the Hot Rolling of Steel in Europe

The advent of modern rolling practice may, however, be said to date from 1783 when a patent was granted to Henry Cort of Fontley Iron Mills, near Fareham, England, for utilizing grooved rolls for rolling iron bars. A mill with rolls of this design could produce at least 15 times the output per day obtainable with a tilt hammer. However, the claim to innovation put forward by Cort and his successors was strenuously contested at a later date. He was not the first to use grooved rolls, but he was the first to combine the use of all the best features of the various steelmaking and shaping processes known at that time. This fact alone justifies the term “father of modern rolling”, which has been applied to him by modern writers.

In the beginning of the nineteenth century, the industrial revolution in England was gathering momentum, creating an unprecedented demand for iron and steel. Accordingly, rolling mill developments were numerous and important. John Birkenshaw started the first rail rolling mill in 1820 producing fish-bellied wrought iron rails in lengths of 15 to 18 feet. In 1831 the first T-rail (of the same basic design as that used today) was rolled in England and the first I-beams were rolled by Zores in Paris in 1849.

Both the sizes of the mills and the sizes of rolled product grew rapidly. At the British Great Exposition of 1851, a plate 20 feet long, 3-1/2 feet wide, and 7/16 of an inch thick was exhibited by the Consett Iron Company. This plate weighed 1,125 pounds and was the largest plate rolled up to that time.

Three-high mills were also introduced about the middle of the century. A British patent for such a mill designed for rolling heavy sections was granted in 1853 to R. B. Roden of the Abersychen Iron Works. In this mill, the middle roll was driven and fixed in the housing while the upper and lower rolls were adjustable in position. On the same mill, a steam-operated lifting table raised and lowered the material to be rolled. This design was improved on a few years later by Bernard Lauth who used a middle roll of smaller diameter than the upper and lower rolls, as illustrated in Figure 1-10. This modification to the mill provided it with a higher productivity with less power utilization.
In mid century, the first reversing plate mill was put into operation at the Parkgate Works in England, and in 1854 it was used to roll the plates for the "Great Eastern" steamship. In 1848, the universal mill was invented by R. M. Daelen of Lendersdorf, Germany, who built the first mill of this type about seven years later. Although patents for "continuous" hot mills were issued to Sir Henry Bessemer in 1857 and to Dr. R. V. Leach in 1859, "the first mill constructed on the continuous principle of rolling iron or steel" was the subject of a patent issued to Charles While of Pontypridd, Wales.

However, an apparently more successful continuous mill was patented in 1862 by George Bedson of the Bradford Iron Works at Manchester, England, in which he claims the employment of a series of rolls placed at varying angles, whereby the necessity of turning the metal is avoided. This was a rod rolling mill in which a 100-pound billet of 1-1/16-inch square cross section was drawn through 16 pairs of rolls in line, 8 horizontal and 8 vertical as illustrated in figure 1-11. Its production rate was such that 20 tons of No. 5 iron wire rods could be rolled in 10 hours.

Figure 1-11: The First Continuous Wire Rolling Mill Developed by George Bedson, 1862.

A British patent issued in 1862 to J. T. Newton of Ystalyfeva, Wales, described a predecessor to the modern cluster mill, in as much as it used small work rolls backed up by others of larger diameter. The work rolls were driven but the pressure was applied by the large backup rolls, a principle utilized in both the hot and cold mills of today.

The four-high mill with its rolls in the same vertical plane was introduced by Bleckley of Warrington, England, in 1872, to finish wrought-iron piles from which rails were rolled. Mills to produce Z-bars were put in use in Germany in 1863, and in 1867, beams 8 to 12 inches deep were rolled on a mill designed by Menelaus, of the Dowlais Works in Wales. This mill contained two pairs of rolls, one pair placed in a vertical plane, somewhat higher than the other pair of rolls. Petin, Gaudet et Cie, Rive-de-Giev, France, was rolling beams on a universal mill in 1872, and four years later, Joseph de Buigne, of France, rolled the first H-beams produced on a continuous mill, utilizing the diagonal method of rolling.

Tandem rolling of hot steel took an upsurge around 1890, and in 1892, a semi-continuous hot strip mill, with a mechanically geared two-high tandem finishing train, was built at Teplitz, Bohemia. It was reported to have rolled sheets up to 50 inches in width, in thicknesses from 0.080 inch to 0.120 inch and in lengths up to 60 feet. The mill utilized a roughing train of two three-high stands and a finishing train consisting of five stands of 24-5/8 inch by 59-inch rolls spaced on 9-foot centers. Each train was powered by a 1,000-HP engine as illustrated in Figure 1-12. Since the works at Teplitz were abandoned in 1907, it is to be assumed that the mill was not a commercial success.

1-3 The Early Rolling of Steel in the United States

To all intents and purposes, the history of metalworking in the United States began with the arrival of colonists from Europe. Since skilled metalworkers were present in every colony, the colonists supplied a great part of their own needs for metals. However, in 1750, the British Parliament decreed that "no mill or other engine for slitting or rolling iron, or any plating forge to

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work with a trip hammer, or any furnace for making steel” should be built in the American Colonies. This law was generally disregarded so that by 1775, the colonies were producing 30,000 tons of iron per year, only one third of which was exported to England as pig iron and bar iron.

The first American rolling mill was built in 1751 for Peter Oliver, one of the Crown Judges in the province of Middlesboro, Massachusetts. It was used to roll down 3-inch wide hammered bars made at the charcoal forges from a thickness of about 3/4-inch to 1/4-inch suitable for slitting into nail rods in 4 passes. The rolls were each driven by an undershot waterwheel 18 feet in diameter with a face length of 10 feet through cogwheels and the speed of the rolls could be matched by adjustment of the gates in the mill streams. The chilled iron rolls were 36 inches long by 15 inches in diameter and were designed with roll necks 9 inches in diameter.

At the outbreak of the American Revolution, the colonies possessed a flourishing iron industry from which all restrictions were ended with the establishment of independence. But it did force competition from a European iron industry with its century and a half of experience. Undaunted and unhampered by tradition, the Americans succeeded, however, within the next two centuries to develop the largest national steel industry in the world.

Some of the more notable steps in the development of the new steel industry were as follows. Isaac Pennoch established a slitting mill on Bush's Run (near Coatesville, Pa.) in 1793, and by 1810 this plant was rolling plates with mills using rolls 16 to 18 inches in diameter and 3 to 4 feet long, driven by an over-shot waterwheel. (See Figure 1-13.) In 1820, Dr. Charles Lukens, Pennoch's son-in-law, rolled boiler plates for the first time at this plant which eventually developed into the present Lukens Steel Corporation.

However, at the beginning of the nineteenth century, it was apparent that the Pittsburgh area was becoming the focal point of the industry. Christopher Cowan built the first rolling mill in Western Pennsylvania, and, incidentally, the first one known to have been powered by steam. It utilized a 70-HP steam engine which also supplied power for a slitting mill and a tilt hammer. At Plumsock (about midway between Connelsville and Brownsville, Pa.) Isaac Meason, in 1816, built the first American mill for puddling iron and rolling flat bars. Two years later, the Pittsburgh Steam Engine Company built a sheet rolling mill, and in 1819, the first angle iron rolled in the United States was produced at the Union Rolling Mill in Pittsburgh. By 1825 five rolling mills were in operation in Pittsburgh and a sixth was under construction.

By the middle of the nineteenth century, iron production in the USA had risen to 350,000 tons per year and the increasing availability of metal fostered considerable inventiveness designed to further process and fabricate metal parts. The rolling of corrugated plates was patented.

in 1850, and in the same year an Ohioan patented an improved machine for rolling irregular forms of metal such as strip hinges, plane irons, elliptic springs, socket chisels, axle trees, shovels, axes, hammers, and spades. (See Figure 1-14.)

The first three-high beam mill in the U. S. was used by the Trenton Iron Works, at Trenton, N. J. Built in 1852, it employed three vertical rolls and the iron was reduced in each pass, in each direction. Another beam mill departing radically from previous designs was supposed to have been built in 1853 by Charles Hewitt of Cooper, Hewitt and Co., Trenton, N. J. However, the first thoroughly satisfactory three-high mill is generally attributed to John Fritz, who built such a mill for the Cambria Iron Works, Johnstown, Pa. in 1857 to roll rails between 18-inch diameter rolls. (See Figure 1-15.) This mill is of interest because it established the practice of mounting the mill housings on heavy, cast guide rails. However, Jones and Lauth of Pittsburgh, Pa. introduced the Lauth mill to the U. S. in 1859 buying all U. S. rights from the British patent owner.

![Figure 1-14: Machine for rolling irregular forms. (Steel Engraving from Scientific American, 1860.)(Drawing in Staffordshire Iron and Steel Institute Proceedings.)](image1)

After the Civil War ended in 1865, the rapid expansion of the railroads proved to be a tremendous stimulus to the American iron and steel industry. The first steel rails were rolled in 1865 by the North Chicago Rolling Mill Company. In 1867, George Fritz (brother to John Fritz) started the first successful blooming mill operation in the U. S. and, in the same year, the first beams were produced in Pittsburgh on a 20-inch structural mill. Also in the same year, Andrew Kloman, with the help of John Zimmer, built the first universal mill in Pittsburgh capable of rolling plates from 7 to 24 inches wide and from 3/10 inch to 2 inches thick. In 1877, Mackintosh-Hemphill designed and installed a 30-inch reversing blooming mill for Schoenberger and Company (later the Schoenberger Works of the American Steel and Wire Company). This was the first mill of its kind in the Pittsburgh area and possibly the first in the United States. In 1881, the firm of Mackintosh-Hemphill, Inc. built the first rolling mill of wholly American construction, this being a two-high reversing blooming mill at the Pittsburgh Bessemer Works (the forerunner of the present Homestead Works of the U. S. Steel Corporation).

The rolling of sheet steel in the United States began around 1880 using mills similar to that shown in Figure 1-16, and it is recorded that a three-high mill with 84-inch long rolls at the Brandywine Rolling Mill (later part of Lukens Steel Corp.) was used for this purpose. Sometime later, the same company installed a three-high roughing mill and a three-high finishing mill, both using chilled iron rolls 34 inches in diameter and 120 inches long.
1-4 Energy Sources for Rolling Mills

The earliest mills, as has been seen in Section 1-1, were operated by handpower, usually by turning a strong-armed cross or an adjustable crank attached to either or both of the rolls. With such limited power available, the only materials that could be rolled were the softer metals such as gold, silver, tin, and lead.

Waterwheels were next used to turn mill rolls, and this was a convenient development since such wheels were widely used in iron works for the operation of bellows. The first mill likely to have been powered by a waterwheel was the slitting mill built at Dartford in Kent, England, in 1590 by Godefroi de Bochs under a patent granted in 1588 to Bevis Bulmer. In the four-high mill erected near Sheffield, England, about 1790, by James Cockshutt and Richard Crawshay, the top and bottom rolls were each driven by separate waterwheels, which were weighed by a heavy stone rim bolted together in segments to act as a flywheel. Figure 1-17 illustrates the use of an undershot waterwheel to drive a plate mill in 1734.

The first commercially successful steam engine was invented in 1698 by Thomas Savery of England, who, incidentally, was the first to evaluate an engine in terms of horsepower. However, his steam engine was not first used to drive the mill rolls but to pump back into the reservoir the water that had already passed over the waterwheel. However, a Boulton and Watt steam engine was used to power a rolling and slitting mill at John Wilkinson's Bradley Works and a steam engine was used to power a tinplate rolling mill in 1798. (See Figure 1-18.)

![Figure 1-18: Earliest drawing of a steam engine to operate a tinplate rolling mill at Lower Redbrook, 1798.](image)

Improvements to steam engines occurred rapidly at the beginning of the nineteenth century and they were soon commonly used for driving mills, the power being transmitted to the rolls by direct mechanical connections through shafts, couplings, and gears. In the latter half of the nineteenth century, there was a constant demand for larger and larger engines so that by 1875, engines were being built capable of delivering in excess of 1,000-HP, some being as large as 3,000 to 4,000-HP units (Figure 1-19).

![Figure 1-19: A valve-side view of the engine designed for Carnegie, Phipps & Company's Homestead Steel Works in 1890. Largest mill engine in America, it was 43-1/2 feet long, had a 27-foot flywheel weighing 90 tons, and developed 3,500 Horsepower. (Iron Age, December, 1890.)](image)

Initially flywheels found extensive use in powering of mills, particularly after the development of 3-high mills (such as the Lauth mill) which required no reversals. It became apparent, however, towards the end of the nineteenth century, that two-high mills with drives
capable of rapid reversal were to be preferred, especially in view of the fact that they could be quickly stopped if necessary.®

Yet steam power, at its best, was costly and inefficient and it was fortunate that the latter part of the nineteenth century saw the development of electric generators and motors. With the generators driven remotely from the mills, electric power could be conveniently transmitted over wires to motors directly attached to the mills. Some of the generators were driven by internal combustion engines as, for example, at the Gary Steel Works. This plant was designed in 1908 to be the first sizable steel mill built for the use of electric power and it had 15 gas-driven generators each capable of outputs up to 2,000 kilowatts. The size was increased a few years later to 3,000 kilowatts equalling the largest reciprocating steam-driven generator at that time.

Even earlier, direct current motors had been installed to operate some smaller mills. In 1903, two 1500-HP motors powered a light rail mill at the Edgar Thomson Works at Braddock, Pa., and the first reversing d-c main drive motor was installed the same year on a 36-inch universal plate mill at South Works in Chicago.

Both gas and steam engines operated at relatively slow speeds which put a physical limitation on generators. For example, 5,000 kw generators so powered had diameters in excess of 30 feet. On the other hand, steam turbines operating at high rotational speeds enabled generators driven by them to be much more compact.

Other improvements in the generation and distribution of electrical power led to a steady conversion to electric motors in steel mills not only in the USA but throughout the world. The use of variable speed d-c motors on main drives began in the early 1940's and has been gaining popularity ever since. At the same time, the power utilized by mills has gradually increased so that some of the more recent hot mill stands are driven by multi-armature motors providing 12,000 horsepower usually enclosed in dust free motor rooms§ (see Figure 1-20). In the case of modern

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Figure 1-20: Motor Room of Modern Hot-Strip Mill Showing Two Triple-Armature Motors In the Foreground.
cold reduction facilities, the stands of wide sheet mills are typically powered by motors of 8,000-HP, which are generally located on the open mill floor rather than in specially-built motor rooms.

1-5 The Historical Development of Cold Rolling

In spite of the fact that the first rolling of metals was, in effect, cold rolling, the flat, cold reduction of iron and steel does not seem to have been successfully carried out until the end of the eighteenth century, although the flat, hot rolling of steel had been undertaken on 2-high mills since about 1660. However, it should be noted that cold rolling, in the form of a planishing operation, was practiced on tin plate in England as early as 1747 and, in 1783, in the same country, John Westwood proposed the cold reduction of steel bands for watch springs. From 1825 to 1860, due mainly to improvement in the manufacture of rolls, considerable amounts of high-carbon flat wire, corset stays, etc., were produced by cold rolling.\footnote{M. D. Stone, "Reversing and Tandem Cold Mills", Iron and Steel Engineer Year Book, 1947, pp. 265-272.}

When the first cold-rolling operations were undertaken in the U.S.A. is uncertain. It appears, however, that the flattening of wire carried out by the Washburn and Moen Company, in Worcester, Massachusetts (later the Worcester Works of the U. S. Steel Corporation) constituted the first commercial operations of this type.\footnote{J. R. Adams, "Hardened and Ground Rolls", Yearbook of the AISI, 1924, AISI, New York, 1925, New York, pp. 115-147.}

The development of the flat, cold-rolling of steel as a production process, however, gained real impetus only after the evolution of the Lauth 3-high cold mill with its smaller diameter middle (work) roll. Yet the advantages of smaller diameter work rolls had been recognized much earlier for Christopher Polhem described a 4-high mill for flat, hot rolling using “slender” wrought-iron work rolls, supported by large cast-iron backing rolls, because “small rolls possessed much more power of stretching (elongating) material than did large ones”. The commercialization of the Lauth cold mill, however, as discussed in Section 1-4, was carried out principally in America by the old American Iron & Steel Company of Pittsburgh, later acquired by Jones & Laughlin.

As the superior properties of cold rolled strip became more and more appreciated, cold rolling spread even more widely both in this country and abroad, being practiced primarily on 2-high and double 2-high mills, although 4-roll and 6-roll cluster mills of the Wilmot and Mann types were later used in this country. The first 4-high mill for the cold rolling of steel was first used on an experimental basis as recently as 1923 by the Allegheny Ludlum Steel Corporation.

Improvements to roll neck bearings also contributed to the increasing use of cold reduction mills. Roller bearings were first used on 2-high cold mills as early as 1890, on the backup rolls of cluster-type cold mills in 1909 and on 4-high mills in 1926.

Reversing cold mills of the 2-high type were first used in Germany in the 1920’s (having been disclosed in the patent literature as early as 1917) and of the 4-high type in 1932. The first such cold mill in this country was installed at Gary in 1933.

The first record of tandem cold rolling of steel strip goes back to about 1904, when the West Leechburg Steel Company installed and operated a 2-high 4-stand tandem mill, each stand being driven by a separate, adjustable speed d-c motor. Real tandem mill operation, with tension between stands, and a tension reel, was developed around 1915, on mills installed by Superior Steel Company and the Morris & Bailey Steel Company of Pittsburgh. And in 1926, the first 4-high, 4-stand tandem cold mill was put into operation by the American Rolling Mill Company at their Butler plant.
In the operation of both reversing and tandem mills, as the strip being handled got longer, and was rolled at higher and higher speeds, the matter of handling the material necessarily demanded attention. This occurred first in the hot rolling of wire rods and the first reels on record were used around 1860, being manually rotated by a boy, who visually synchronized the reel with the mill. These reels were however, subsequently mechanized. The cold strip reel seems to have preceded the hot strip reel or coiler by some ten years, the first cold reels being built in Germany by August Schmitz Company, around 1893. The reels were well designed units, having wedge-type collapsing segments, and driven from the mills by slipping belts for tension control. The first high-tension reel, as such, was patented in 1905 by W. F. Conklin, of Pittsburgh, using a slipping friction clutch. Around 1920, the separate, electrically-driven reel, maintaining constant tension by current control, was developed jointly by the Superior Steel Company and the Westinghouse Electric Corporation.

The concurrent development of reels and the electric drive resulted in the development of strip tension control, first between mill and reel, and later between adjacent stands of the tandem mill. Although the first tandem cold mill was operated with slack strip between stands, the art was later advanced to the using of slack or loop take-ups, and finally to the adoption of high interstand tension around 1920.

As late as 1930, Shannon* stated, “It should be remembered that ordinarily sheet steel receives its shaping entirely in hot rolling, the cold rolling of sheets being merely a surfacing, flattening, or stiffening operation. . . . In this connection, another recent development requires mention. Within the past few years, cold rolls have been designed which will actually thin down and draw out steel sheets of considerable width while cold; in other words, these powerful rolls will effect cold reduction and consequently are capable of shaping cold steel into sheets of predetermined thickness and length, which cannot be done by the ordinary sheet cold mills. These newly developed mills are not widely used yet, however, so the statement that sheets receive their shaping from hot rolling still holds good for the sheet industry as a whole. Nevertheless, before many years, the cold rolling of sheets may undergo radical changes and developments.”

The last words of the quotation indeed proved to be prophetic because of the extensive use of tandem and reversing cold mills for the production of sheet and tinplate products. However, it must be realized that hot rolling must still be used in reducing an ingot to a strip with a thickness on the order of a quarter of an inch. Attempts to cold roll strip of greater thickness would necessitate excessive rolling forces and energy requirements.

1-6 Modern Primary Cold-Reduction Facilities

In the 1930's, the cold reduction of hot-rolled steel strip evolved from a rather specialized, small-scale process to a position of prime importance in the production of cold-rolled bars, sheet and strip. These products differ from each other principally in dimensions as defined in Table I.

The maximum available widths of cold-rolled strip increased rapidly from 1925 onwards as illustrated in Figure 1-21, and the minimum thickness for a given width decreased. • By 1937, the thickness-width limits for both hot- and cold-rolled strip had reached values shown in Figure 1-22, • and today flat-rolled products are available in even greater width-to-thickness ratios than those corresponding to Figure 1-22.

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### Table 1
Product Classification by Dimensions of Flat, Cold-Rolled Carbon Steel

<table>
<thead>
<tr>
<th>WIDTH (Inches)</th>
<th>THICKNESS, (Inches)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2500 and Thicker</td>
<td>0.2499 to 0.0142</td>
<td>0.0141 and Thinner</td>
</tr>
<tr>
<td>To 12, inclusive</td>
<td>Bar</td>
<td>Strip(^1,2)</td>
<td>Strip(^1)</td>
</tr>
<tr>
<td>2 to 12, inclusive</td>
<td>Bar</td>
<td>Sheet(^3)</td>
<td>Strip</td>
</tr>
<tr>
<td>Over 12 to 23.9375, inclusive</td>
<td>Strip(^2)</td>
<td>Strip(^2)</td>
<td></td>
</tr>
<tr>
<td>Over 12 to 29.9375, inclusive</td>
<td>Sheet(^4)</td>
<td>Sheet(^4)</td>
<td>Black Plate(^4)</td>
</tr>
<tr>
<td>Over 23.9375</td>
<td>Sheet</td>
<td>Sheet</td>
<td>Black Plate</td>
</tr>
</tbody>
</table>

1) When the width is greater than the thickness with a maximum width of 0.5 inch and a cross-sectional area not exceeding 0.05 sq. inch and the material has rolled or prepared edges, it is classified as flat wire.

2) When a particular temper as defined in A.S.T.M. specification A109, or a special edge, or a special finish is specified, or when single strand rolling is specified in widths under 24 inches.

3) Cold-rolled sheet coils and cut lengths, slit from wider coils with slit edge (only) and in thicknesses 0.0142 inch to 0.0821 inch inclusive, carbon 0.20 per cent maximum.

4) When no special temper, edge or finish (other than “Dull” or “Luster”) is specified, or when single-strand rolling widths under 24 inches is not specified or required.

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**Figure 1-21:**
Maximum available width of cold-rolled strip.

**Figure 1-22:**
Chart Comparing the Limits of Rolling Prior to 1923 and the years following.
Typical of the sheet mills built in the 1930's is the three-stand, 84-inch tandem mill shown in Figure 1-23. This mill utilized 20-1/2 inch diameter work rolls, 56-inch diameter backup rolls, and was driven by motors totalling 6,850-HP at speeds up to 542 feet/minute.

Just before and subsequent to World War II, four-stand sheet mills came into vogue, but in the 1960's five-stand sheet mills were built as discussed in Chapter 2.

For tinplate production (with final thicknesses of rolled strip on the order of 0.010 inch) five-stand tandem mills soon came into use in the 1930's. Such a mill installed at the Irvin Works in 1941 used 21 inch and 53 inch by 48 inch rolls and possessed a total motor drive of 11,100-HP. (See Figure 1-24.) It could deliver strip at speeds up to 3,750 feet/minute. Later mills for tinplate production utilized larger motors and were generally operated at speeds up to 5,000 feet/minute. Six-stand tin mills were introduced in the 1960's with still more installed horsepower and slightly larger workrolls (23 inch as compared with 21 inch diameter). Twin drives are used on such mills and they are operated partially under the control of computers.

Although tandem cold mills constructed in recent years have utilized conventional 4-high mill stands, a unique tandem mill facility specifically designed for rolling stainless sheet products up to 50 inches wide was put into service in 1969 by Nissin Steel Company at the Shunan Works located in Nanyo, Japan. This mill was the first mill designed for fully continuous operation with the incoming coils fed from pay-off reels through a welder to be joined head-to-tail. It utilizes a train of 6 stands, the first and last stands being 2-high mills and the intermediate stands

being Sendzimir mills, one being a type ZR-22N-50 and the other three type ZR-21B-50. A more detailed description of this mill is presented in Section 2-15.

Another fully continuous cold mill for rolling steel strip was put into operation in 1971 at Nippon Kokan’s Fukuyama Works in Japan.* This mill also features two pay-off reels, a shear, welder, strip accumulator, five mill stands, a flying shear and two tension reels. Coils to be rolled are welded end to end and, during the welding operation, strip continues to be drawn from the accumulator. The mill utilizes 4-high stands (with hydraulic cylinders in stands 1 and 5 for rapid roll positioning), is as fully automated as present technology permits and is under computer control. Further details of this mill are presented in Section 2-15.

For stainless and silicon steel rolling and for the processing of special alloys with limited markets, single-stand reversing mills (particularly Sendzimir mills) have continued to find popularity. Such mills usually feature powerful main drives (up to 8,000-HP or more) and motors attached to the reels supplying power approximately equal to half that of the main drive motor.

The foregoing mills, discussed in greater detail in Chapter 2, are operated differently from their early slow speed predecessors in a number of ways. High strip tensions are now usually used (whereas in some of the first tandem cold mills, free loops of strip were developed between the stands) and rolling lubricants were found to be necessary. Such lubricants (generally oils such as palm oil or cottonseed oil) were found to greatly facilitate the rolling operation in reducing rolling forces and lessening the rolling energy required. An aqueous recirculated mixture of the rolling lubricant (generally called a rolling solution) was used not only to provide the lubricity in the roll bite between the roll and strip surfaces, but also acted as a coolant for the rolls and the strip being rolled.

Mill speeds have also increased considerably but coincident with this has been a steady improvement in rolled strip quality. Automatic gage control systems have maintained good

uniformity in the thickness of the rolled product and improved lubricants have maintained strip coiling temperatures within permissible limits. Although shape problems still reoccur in rolling operations, roll grinding techniques have improved so that, together with better mill instrumentation, such problems become less frequent.

1-7 Secondary Cold Rolling Mills

Just prior to 1960 double-reduced tin plate was commercialized in the U.S.A. as a packaging material. This light-gage steel strip is rolled on specially designed cold mills variously designated as “secondary cold mills”, “DCR (Double Cold Reduction) mills”, 2-CR (Secondary Cold Reduction) mills and sometimes as “skinny-tin mills”. One-, two- and three-stand mills have been used for this purpose, with the two-stand mills being the most popular (see Figure 1-25).

Figure 1-25: Two-Stand Cold-Reduction Mill Viewed from Operator’s Side

The first method of manufacturing double-reduced tin plate involved the following steps; 1) primary cold reduction, 2) electrolytic cleaning, 3) box annealing, 4) tinning, 5) secondary cold rolling (with a reduction close to 50 per cent), 6) cleaning, 7) chemically-treating, and 8) oiling.* It soon became apparent, however, that due to equipment and processing conditions peculiar to each producer, differences in appearance and lustre of the matte-like surface did exist and created problems for the can manufacturer in matching surface appearance (particularly with respect to the lithographing of the tin plate) from the various producers. As a consequence, the product was soon made by reducing box-annealed black plate 30-40 per cent and tinning this light gage steel strip in the conventional manner. Today, it is sold commercially in gages ranging from approximately 0.005 to 0.011 inches in thickness (45-100 lb/base box).

* W. L. Cooper, “Double Reduced Tin Plate”, Yearbook of the AISI, 1964, pp. 147-163.
Although the stands of a secondary cold reduction mill generally resemble those of a primary cold-reduction facility, there are some significant differences. The maximum speeds of these mills are generally less than those of primary cold rolling facilities, and for this reason, as well as the fact that the drafts are relatively small, the drive power required is appreciably less in secondary than in primary cold-rolling mills. On the other hand, the strip width-to-thickness ratio is larger so that the lubricity provided by the rolling lubricant becomes more critical. Moreover, because of the light-gage of the rolled product, the mill must be designed so that excessive tensile stresses are not developed in the strip. Lastly, both the surface finish and the shape (see Chapter 11) of the final product must be exceptionally good otherwise surface defects will be visible through a coating (such as a chromium-chromium oxide or “tin-free-steel” coating) and the sheared product could not be satisfactorily handled on can-making lines.

Very recently, the drawn-and-ironed (D & I) can made out of both conventional black plate and tin plate has been developed to a successful stage. In the course of manufacture, the steel, given a primary cold reduction and annealing, is in effect given a “secondary cold reduction” in the drawing and ironing operation. It is conceivable, therefore, that the drawn-and-ironed can could significantly influence the future status of the secondary cold reduction mill.

1-8 Foil Mills

In recent decades, various metals have been rolled to very light gages for such applications as packaging, capacitor manufacture, and printed circuit boards. For virtually all these applications, however, the quantity of rolled product was limited and coil widths of a few inches usually sufficed. Accordingly, small mills (often Sendzimir mills) were used in making such specialized foils in thickness often in the range 0.0001 to 0.001 inch.

Soon after 1960, however, it became apparent that a reasonably large market existed for relatively wide (up to 30 inches or more) steel foils. A foil mill capable of rolling tin coated strips down to a thickness of 0.0015 inch and less in widths up to 30 inches or more was therefore installed at the Gary Works of the U. S. Steel Corporation in 1965 (see Figure 1-26).\(^\text{9}\) This single-stand mill and its rolling lubrication system are described in detail in Section 2-18 and the product characteristics presented in Chapter 12.


\(^\text{1}\) “Tin Coated Steel Foil Available in 0.002-Inch Gage from U. S. Steel”, Iron and Steel Engineer Year Book, May, 1964, p. 168.
1-9 Temper or Skin Pass Mills

In Section 1-5, the early use of cold mills to planish tin plate was noted, such mills constituting a type of temper or skin-pass mills. Basically such mills give a very light reduction to annealed stock so as to provide a degree of surface hardening, restore temper and prevent stretcher strain or the breaking of the surface in subsequent drawing operations. In addition, temper mills are used to impart a desired finish or luster to the surfaces of the workpiece and are frequently used to impart the desired degree of flatness to the rolled product.

Usually temper mills are operated without a rolling lubricant. This is fortunate in that the rolled surfaces of the strip remain virtually uncontaminated and, therefore, ready for further processing (such as tinning). Moreover, the high friction occurring in the roll bite between the roll and strip surfaces ensures that only a very limited elongation or reduction is given to the workpiece.

Occasionally, however, temper mills are operated “wet” either for the purpose of achieving a larger reduction than would otherwise be obtainable and/or with the intent of leaving a lubricating, corrosion-resistant or other type of film on the surface of the temper rolled material.

Temper mills for the rolling of sheet products have traditionally utilized a single-stand as illustrated in Figure 1-27 while two-stand mills are commonly used to produce the harder tempers required for tinplate products.

![Figure 1-27: Single-Stand, Four-High Sheet Temper Mill, for Temper Rolling Flat-Rolled Steel in Coil Form. Product Travel Through the Mill is from Right to Left.](image-url)
In recent years, there has been a tendency to utilize one rolling facility for two or more different types of rolling operations. For example, single and two-stand mills have been installed to carry out both cold reduction and temper rolling operations (see Figure 1-28). In such facilities, provision is usually made to accommodate sets of work rolls of different sizes, smaller diameter rolls being used for normal cold rolling operations and larger rolls for temper rolling.

Figure 1-28: Combination Cold Reduction — Temper Mill.