Progress of Strip Casting Technology for Steel; Historical Developments

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With increasing competition in the global steel market, strip casting technology potentially offers an efficient, economical and environmentally-friendly approach to the production of hot-rolled, coiled steel. This review provides a summary of the basic theory and history in the developments of strip casting operations of steels, along with technical discussions regarding various strip casting initiatives that have been carried out in the past, as well as present. Two strip casting processes are discussed in detail; Twin-Roll Casting (TRC) and Horizontal Single-Belt Casting (HSBC). With its inevitable logic, the emergence of strip casting technology could have an enormous impact on the world’s steel industry. This present paper reviews the progress of strip casting technology for steel from a historical perspective, and this will be followed by a sequel, reviewing recent technical developments in the field.

KEY WORDS: strip casting; belt casting technology; horizontal single-belt casting; twin-roll casting; near net shape casting.

1. Introduction

Strip casting is a form of Near-Net-Shape Casting (NNSC) technique. NNSC generally refers to those casting processes in which the cast products possess dimensions close to the final products, so that post-casting size-reduction and finishing steps can be minimized. Strip casting, in particular, is defined as the casting of molten metal into metal strips (thickness in the order of several mm) in a single processing step, which may subsequently be hot-rolled, in-line (if required), into thin-steel of desired product thickness. Since the strip casting process integrates casting and rolling into a single process, the slab re-heating and repeated hot-rolling steps required in conventional hot-steel production can be eliminated. This can provide many economic, environmental and technical benefits to the steelmaking industry, thus making strip casting a “holy grail” for the steel industry.

2. Overview of Strip Casting

Steel strips with thicknesses in the order of millimeters are common products of the steel industry. The process by which hot-rolled coiled steel, or hot strips, is produced, has evolved greatly over the past several decades, resulting in progressively higher efficiency and productivity. Before the 1960’s, ingot casting was used to produce steel strips. Molten steel would be cast into large steel ingots using a cast iron moulds in batches of a hundred or more, and subsequently transported to a breakdown mill where they were reheated and processed into slabs 20–30 cm thick using a roughing mill. These semi-finished products usually had to be reheated following scarfing and undergo seven steps of size reduction in the “hot mill” or seven-stand hot rolling mill, to produce hot strips of the desired thickness.

The invention and subsequent implementation of the Conventional Continuous Casting (CCC) process in the 1970’s enabled molten steel to be made directly into semi-finished forms of thick slabs (200–400 mm) continuously. This eliminated the need for expensive breakdown/roughing mills and greatly improved the efficiency of production and yield by turning the casting process into a continuous operation.

In 1989, the Thin Slab Casting (TSC) process was invented and slabs of 50–60 mm thick could be cast directly from the melt. Casting and hot-rolling were integrated into one continuous process, where thin slabs were passed into a reheating furnace directly and then hot-rolled in-line, into strips, immediately after. As a result, the cost of reheating and rolling was considerably reduced. Strip casting technology aims to produce as-cast steel that is even thinner, directly from the melt, so that reheating can be eliminated altogether, and the cost associated with rolling can be minimized.

The evolution of hot strip production technology is summarized in Fig. 1. As can be seen, technological innovation in production technologies have resulted in dramatic decreases in equipment size and processing stages, which translates into significant reductions in both capital and operating costs.

Like other casters, a strip caster consists of a tundish and a mould. The molten steel is transferred from a ladle into the tundish where it is shielded from oxidation and held at an appropriate temperature. The holding vessel (tundish) delivers molten steel via the submerged entry nozzle (SEN), or a more sophisticated arrangement such as a melt dispenser, into a mould, where it solidifies to form steel strips. The defining feature of strip casters is the ‘moving mould’ design, where the mould surface moves along with the solidifying melt, thus minimizing the relative speed difference between the two surfaces. Nonetheless, several distinct strip casting technologies exist today: Single- and Twin-Roll
Casting (SRC and TRC), as well as Single- and Twin-Belt Casting (SBC and TBC). The schematics of these mould designs are shown in Fig. 2. Group I are the Belt Casters (BC’s) which uses water cooled travelling moulds or conveyor belts. Liquid steel is cast directly onto a belt (i), or sprayed (ii), or cast between two belts either inclined (iii) or vertical (iv). Group II casters use a Single Roll (SRC) to produce thin-gauge strip. Two different feed systems are typically used, melt-spinning and melt-drag. Group III comprises the Twin Roll Casters (TRC) of various configurations: vertical (i), horizontal 2-high (ii), horizontal 4-high (iii), inclined and (iv), asymmetrical twin rolls (v).

3. Historical Developments

The original idea of directly producing metallic strips from molten metal was conceived by H. Bessemer. The concept of strip casting attracted Bessemer’s attention in early 1846. By 1857, Bessemer had patented his twin-roll caster design for steel, based on an existing twin-roll caster made for producing tin foils and lead strips. In 1865, he patented a TRC caster designed for iron and steel strips. Despite successful experiments, various mechanical difficulties and an accidental fire in Norton’s workshop made him conclude that further investment in his continued development was not justified. Thirty years later, in the 1920’s, research into Bessemer’s design regained popularity and several projects were undertaken, both in the West, as well as in the former USSR. The most prominent project was by Clarence W. Hazelett. Commercial twin-roll casters designed for lead, aluminum and brass strips were successfully built by Hazelett and met with considerable success. When Hazelett attempted to cast steel strips, however, he encountered many problems associated with cast strip quality and roll materials. At first he tried to overcome this problem by resorting to a single-roll caster, but was then faced with other problems, such as strip thickness variability, cast quality and edge containment. As a result, Hazelett abandoned his development of single- and twin-roll strip casting in the 1940’s, and concentrated on the development of twin-belt casting. His new research direction met with immense success, so much so that modern twin-belt casters are colloquially known as Hazelett casters and are widely available commercially for the casting of many different metals, with the exception of steel.
After the Second World War, global steel production increased substantially, rising from 113.1 Mt/yr (million metric-tonnes per year) in 1945 to 645.4 Mt/yr in 1975.10) Most of these demands were met by large integrated steel mills, producing over 5 Mt/yr.11) The large demand for steel for post-war reconstruction shifted the steel market into one dominated by supply. The Conventional Continuous Casting (CCC) process was commercialized in 1952 by Mannesmann and introduced, globally, to integrated mills in the 1970’s.12) It was rapidly accepted, given the 10% increase in steel yields possible versus ingot casting technology. The effectiveness of the new CCC technology also lessened the desire of steelmakers to invest in the development of strip casting technologies for steel.

On the non-ferrous side however, the development of strip casting technology for light metals continued. Hunter and Pechiney became leaders in the development of twin-roll casters for aluminum alloys during this time. The first commercialized twin-rolled caster for aluminum alloys, the Hunter Standard Caster, was introduced in 1954 by Hunter, using the upward-vertical twin-roll design.13) In 1962, Pechiney developed the world’s first horizontal twin-roll aluminum caster, the Harvey Caster. In 1970, the new horizontal twin-roll caster with a 15° upward tilt was introduced by Hunter. The basic design schematics for these three casters are shown in Fig. 4.

These 1st generation designs would develop into 2nd generation casters (1975–), including Hunter’s Super Caster and Pechiney’s Jumbo3C, and later into 3rd generation casters (1992–) such as Hunter’s Speed Caster/Speed Caster Plus, and Pechiney’s Jumbo3CM, which cast at very low speed (~1–2 m/min). Newer caster designs such as the Davy Fastcast, utilizing four rolls, were also developed during this period.14) Today, twin-roll casting is a popular method of commercially producing thin strips of aluminum alloys. The advancements in multi-roll casters for light metals since the 1950’s is an important milestone for the development of strip casting technology as a whole, but is nonetheless beyond the scope of this review, which emphasizes the strip casting technologies for steel.

After two decades of global prosperity, the steel market in the USA began to deteriorate from about 1970’s onwards.15) World steel prices were pushed down as the combined effects of over-capacity, increased energy costs (contributed by the 1973 Oil Crisis and later the 1979 Energy Crisis), privatization of national steel companies, and increasing competition from other materials, forced the steel market to become progressively more demand-dominated and increasingly competitive.16) Restructuring within the industry became much needed, with strong emphases on efficiency, just-in-time management and competitiveness. Similarly, production flexibility and quality also gained importance.17) R&D initiatives aimed at improving both the process and its products grew, as steelmakers sought to achieve more compact steelmaking technology with lower capital costs for smaller steel plants. Co-operative development with suppliers and customers was also undertaken during this period.18,19) Studies have shown that during this time period, steelmaking firms spend as much as 2.5 billion USD annually on R&D, representing approximately 1% of their revenues.11)

Among other initiatives, there were intense R&D activities concentrated on near-net-shape casting processes.20) Over a hundred research initiatives were made between 1975 and 1985, as steelmakers sought for a technological innovation that could extend the advantages of continuous casting.21,22) Many previously abandoned technologies were re-examined during this period, including Bessemer’s twin-roll caster design and Hazelett’s twin-belt caster design.23) The most promising technology during this period was the Hazelett caster, which had been used for R&D as early as the 1960’s.24) The technical difficulties that impeded its development back then were re-evaluated, and believed to be not inherent to the caster. Consequently the R&D initiatives were renewed.25)

Many steelmakers across the world favoured the development of Hazelett-style twin-belt casters for steel, including Krupp Stahl and Mannesmann from Germany, British Steel from UK, Bethlehem Steel, and US Steel from the US. Similarly, many Japanese steelmakers such as Nippon Steel, Mitsubishi, Kawasaki, Kobe Steel, Sumitomo Metals and Hitachi Zosen were of like mind.26)

However, with the successful emergence and commercialization of Thin-Slab Casting (TSC) technology developed by SMS, and its subsequent implementation at Nucor in 1989, the development of twin-belt steel casters again became redundant since TSC process was capable of casting steel within the same thickness range.27) Nevertheless, the success of TSC did not prevent some steelmakers from further developments of strip casting technologies capable of realizing thinner products. However, by 1985, the majority of R&D efforts in twin-belt, initiated over the previous decade, had been terminated,28) leaving behind only the most competitive and viable technologies.

4. Recent Developments

Many strip casting R&D projects have been initiated worldwide since 1980. The most popular design was Bessemer’s Twin-Roll Caster (TRC) concept. A few processes have since been successfully commercialized, such as the Castrip process and POSCO’s poStrip process. The Horizontal Single-Belt Casting (HSBC) design has also gained prominence recently, with successful lab- and pilot-scale casters constructed and industrialization in sight. There have been several R&D projects for twin-belt and single-roll strip casters for steel, but they were eventually abandoned, either because of technical difficulties, or in favour of the other designs such as TRC.

This section of the review will focus on the development of strip casting technology for steel products made since 1980. For this, we closely examine the various projects that have gained prominence since then.
4.1. Allegheny Ludlum (US), Voest-alpine Industrieanlagenbau (VAI, Austria) – Single and Twin-roll Casting

Allegheny Ludlum began their development of the single-roll caster for specialty steels as early as 1982. Allegheny favoured the single-roll design, due to their prior R&D experience with rapid solidification.\(^{(15)}\) In 1984, Allegheny shocked the steel industry by announcing that they had successfully developed a strip casting process.\(^{(2)}\) On the other hand, VAI, the US-based Austrian machine supplier, had been developing both TSC and strip casting processes since the mid-1980's. VAI continued to develop single- and twin-roll casters. VAI's research found twin-roll casting to be more challenging than single-roll casting in their development dedicated to the casting of carbon steel.\(^{(13)}\) Seeking a machine supplier to construct a pilot caster, Allegheny approached VAI and an agreement was signed in 1988 to form a joint development effort.\(^{(15,16)}\) With VAI's experiences in the casting of carbon steel complementing Allegheny's expertise with stainless steel, the joint venture was seeking to commercialize the process by the mid-1990's.\(^{(11)}\) In 1990, work on a pilot caster named Coilcast at Allegheny's Lockport site began.\(^{(16)}\) Although the project claimed a 75% capital cost reduction over the CCC process, Coilcast was shut down in 1994 and Allegheny terminated its strip casting R&D, without issuing a public statement.\(^{(1)}\)

4.2. Armco (US) – Single-roll Casting

In 1983, Allegheny's strip casting R&D gained the attention of the US Department of Energy (DOE), and the DOE decided to support feasibility studies on strip casting, due to its potential for substantial energy-savings. Allegheny's research was beyond the initial stage and it was disinterested in government support. Subsequently, four other teams were given government assistance in their studies.\(^{(18)}\) One of the teams consisted of US Steel and electronics producer, Westinghouse, who focused specifically on the single-roll caster.

In 1984, Westinghouse was chosen for the second phase of the study because its research focused on carbon steel strip casting. This offered the most energy-saving potentials.\(^{(11)}\) US Steel left the project in favour of developing Hazelett-type thin slab casters (which also received government support), and Westinghouse approached Armco, who had undertaken R&D with Hazelett casters, and was interested in developing a single-roll caster.\(^{(14)}\) The contract was extended to a third and fourth phase in 1988 and 1991 respectively, and Armco eventually became the main contractor.

The DOE contributed approximately 12 million US$ to the project, equivalent to 70% of the total expenditure, while Westinghouse and Armco retained patenting rights for their findings.\(^{(13)}\) Armco was half-way through the fourth phase of the contract in 1993 when it sold its carbon steel division and was restructured into AK Steel Holding Corp. This resulted in the termination of Armco's participation in the project. Besides corporate reasons for abandoning development, R&D results also made Armco believe that TRC was the better strip casting design.\(^{(1)}\)

4.3. Project Bessem and Industrial Materials Institute (IMI, Canada) – Twin-roll Casting

IMI began its strip casting R&D in 1987, motivated by potential interest from Canadian steelmakers. By 1989, a consortium of six Canadian steelmakers (Algoma, Dofasco, Ipsco, Ispat-Sidbec, Ivaco and Stelco, accounting for 80% of Canada's steel production) formed a team to conduct a project known as 'Projet Bessemer'.\(^{(17,18)}\) The consortium charged IMI to carry out R&D on the strip casting of steel, favouring the twin-roll technology and choosing carbon steel as the main grade.\(^{(15,17)}\) In the summer of 1992, a hot model was successfully installed by Hatch and Associates, a Canadian engineering consulting firm. From 1989 to 1992, a research program was initiated by the consortium with the financial support of the Canadian National Research Council.\(^{(11)}\) The objective was to develop a strip casting process capable of producing cheap, high quality, carbon steel. In 1990 and 1992, two hot-model scale casters were started up in Boucherville.\(^{(15)}\) The main caster of Project Bessemar was able to produce carbon steel strips 2–5 mm thick and 200 mm wide, while a smaller caster was used to cast 100–150 mm wide nonferrous alloy strips.\(^{(15,17)}\)

In January 1997, the rights to design future strip casting plants was assigned to Hatch.\(^{(1)}\) However, the program was halted in June 1998, despite the 40 million CA$ of investment made over the 10 years of development, and there are no signs that any member firm was interested in continuing it.\(^{(1)}\) Factors that contributed to the stoppage included: the apparently successful commercialization of the Castrip process for carbon steels; secondly, several of the Canadian steelmakers involved had invested in thin-slab casters; thirdly, the lack of involvement from machine-manufacturers, and finally, the substantial amount of further investment (~100 million CA$) required for an industrial caster.\(^{(1,17)}\) Nevertheless, the consortium's original goal of keeping up with advances in strip casting technology was successful, as the knowledge gained from the fairly restricted investment, was considerable.\(^{(1)}\)

4.4. Other North American R&D Initiatives – Twin-roll Casting

Besides the then Allegheny Ludlum and Armco initiatives, several other US steel companies had also investigated strip casting technology in the early-1980s. One of the more conspicuous projects was by Bethlehem Steel, who began twin-roll caster research as early as 1981.\(^{(1)}\) In 1986, a partnership was formed by Bethlehem with Armco, Weirton and Inland Steel as well as the Argonne National Laboratory, all sponsored by the DOE.\(^{(15)}\) They were charged with solving the edge containment problem.\(^{(19)}\) However, the effort failed to find a solution and it was unable to cast reproducible grades of steel. By 1984, all major strip casting R&D in the US was terminated.\(^{(15,16)}\) In April 1998, strip casting research in the US was restarted when Carnegie Mellon University (CMU) and the American Iron and Steel Institute (AISI), lead a three year, international, multi-partner R&D program, within the ‘Industries of the Future’ Initiative of the DOE.\(^{(12,22)}\) The partners included: Max Planck Institute (Germany). AK Steel (US), British Steel R&D lab (UK), VAI, Dofasco (Canada), LTV Steel Company (US), USX-US Steel Group (US), National Steel Corporation (US), and SMS-Demag (Germany-US). The objective of the project was to determine the potential of strip casting for the US steel industry, to investigate the advantages of strip casting, and to evaluate the possibility of producing new steel grades.\(^{(1,22)}\)

The investigation was claimed to be completed in 2001, and became part of the AISI/DOE Technology Roadmap Program. Although it concluded that strip casting has great potential and is highly feasible economically, no direct follow-up research projects or industrial partnership developed from this particular project.\(^{(1,22)}\)

4.5. Usinor-Saclilor (France) and Thyssen (Germany) – Twin-roll Casting

Both Usinor-Saclilor and Thyssen began experiments on strip casting in the mid-1980s.\(^{(17,24)}\) At Usinor, both single-
and twin-roll casters were evaluated, and after sufficient simulation and design works, the construction of a lab-scale caster began in 1986 at IRSID (Institut de Recherches de la Sidérurgie).\textsuperscript{15} IRSID research had found twin-roll technology to be more promising. From 1986 to 1990, IRSID received some 10–15% R&D support through the European Community on Steel and Coal (ECSC)’s research program.\textsuperscript{1,25} Thyssen, the German integrated steelmaker, co-operated with Institut für Bildsame Formgebung (Institute of Metal Forming) at the Aachen Institute of Technology (RWTH) and built its own lab-scale hot model by 1988.\textsuperscript{24} Tests were done with both single- and twin-roll casters and twin-roll technology was considered more feasible. Thyssen’s research effort received support from German state governments.\textsuperscript{26}

In 1989, the two companies combined their efforts in strip casting research to form a new project called Myosotis, in order to share the capital cost for the pilot caster.\textsuperscript{26} The 10-ton pilot caster was built by the French machine-maker, Cleccim, in Usinor’s stainless steel plant in Isbergues, France. The first hot-test began in June 1991, producing 865 mm wide, 2–4 mm thick steel strips.\textsuperscript{1,17,27} The ladle capacity of the pilot caster grew steadily and reached 92-ton by October 1995. The main steel grade for the Myosotis project was stainless steel, although casting experiments with carbon and silicon steel were also performed.\textsuperscript{1,28} By 1997, the project was such a success that the Usinor and Thyssen began looking into its commercialization.\textsuperscript{26,28} The Myosotis project was later merged into the Eurostrip project, following corporate mergers, and eventually reached industrial scale operation in the 2000’s.

4.6. Centro Sviluppo Materiali (CSM, Italy) and Acciai Speciali Terni (AST, Italy) – Twin-roll Casting

Centro Sviluppo Materiali (CSM), the national research institute for the Italian steel industry, and the Italian steelmaker Acciai Speciali Terni (AST) began the development of twin-roll strip casting for stainless steel in 1985. After two years of feasibility studies, a lab-scale hot-model was designed and constructed in Rome which operated from 1987 to 1998.\textsuperscript{1,32} By 1989, a pilot caster was built in AST’s Terni steelwork with the involvement of the Italian engineering firm INNSE (Innocenti Sant’Eustacchio S.P.A.). In 1993, the team predicted industrial operation in three years.\textsuperscript{1,17} However, according to reported results from the pilot caster in 1995, the surface quality of the strips did not match that of its conventional equivalents.\textsuperscript{29}

The research carried out at CSM was paid for by AST and INNSE, with 20–30% of the budget sponsored by the ECSC.\textsuperscript{1} In 1995, VA1 joined the venture as an equal partner and was involved in upgrading the Terni pilot caster to industrial scale, bringing into the project its previous experience in strip casting. The Terni caster was then capable of producing 2–5 mm thick, 860 mm wide steel strips.\textsuperscript{17} In September 1996, the construction of the industrial caster received 4.5 million € of sponsorship from the European Commission (EC) over a period of three years since the project demonstrated improved energy efficiency.\textsuperscript{30} The AST-CSM project was merged into the Eurostrip process in 1998.

4.7. Krupp Stahl AG (Germany) and Nippon Metal Industry (NMI, Japan) – Unequal Rolls

Nippon Metal Industry began developing twin-roll casting for stainless steel in 1980. In 1986, it established a joint R&D project with Krupp Stahl AG. Their process is unique in that the casting rolls were of different diameters.\textsuperscript{25} By 1987, the caster was able to produce 1–4 mm thick stainless steel strips at a casting speed of 40 m/min.\textsuperscript{31} By 1990, two pilot casters were operational, one in Japan and one in Germany, with the involvement of the German equipment manufacturer Sundwig Eisenhütte Maschinen-fabrik GmbH & Co. (now ANDRITZ METALS – Sundwig).\textsuperscript{1,15}

Krupp’s research was supported by the ECSC and the German state governments.\textsuperscript{1,25,31} In 1992, Krupp merged with another German steelmaker, Hoesch AG to become Fried. Krupp AG Hoesch-Krupp. Organizational changes and the large additional investment required, made Krupp terminate its strip casting project and NMI subsequently cancelled its research around 1995, as well.\textsuperscript{1,15}

The newly formed Krupp-Hoesch would merge with Thyssen in 1999 into the conglomerate Thyssen-Krupp. By 2000, ThyssenKrupp would own 15% of CSM and all of AST, most likely inheriting their strip casting research progress, thus holding stakes in all three of the major European strip casting projects (Myosotis, CSM/AST, Krupp).\textsuperscript{31}

4.8. British Steel (UK) – Twin-roll Casting

Strip casting research at British Steel began in 1986 at its Teesside Technology Centre.\textsuperscript{5} Technical development with a lab-scale model for casting of both carbon and stainless steel grades were undertaken.\textsuperscript{1,11,17} In 1990, the small hot model was upgraded to a larger one with the help of Davy, a UK engineering firm who had experience with strip casting of aluminum. The new caster was able to produce 2–6 mm thick steel strips, 400 mm wide. British Steel experimented with many innovative technologies, such as rheo-casting and low superfate feeding. Nonetheless, all these were abandoned in favour of conventional methods.\textsuperscript{17}

The main drive behind British Steel Stainless’ strip casting research effort was the possibility of integrating casting with cold rolling, owing to its then lack of a hot-rolling facility. After the 1992 merger of British Steel Stainless and the Swedish stainless steel producer Avesta, the addition of a hot-rolling mill lessened the need for strip casting technology. With the loss of British Steel’s stainless steel division, British Steel Teesside shifted its research focus towards the TRC strip casting of carbon steels.\textsuperscript{1,15}

Nevertheless, British Steel continued its development, but re-defined its objective towards merely obtaining the expertise to become an ‘educated customer’ when purchasing future commercialized strip casters.\textsuperscript{1} The majority of strip casting R&D carried out by British Steel received funding from the ECSC. Furthermore, British Steel was involved in three individual projects, as well as two more ECSC supported ventures with several European firms on strip casting of carbon steels.\textsuperscript{29}

4.9. Hitachi Zosen and Pacific Metals (Japan) – Twin-roll Casting

The Japanese machine-maker, Hitachi Zosen, had begun occasional experiments with TRC since 1981. More serious activities were started in 1985 and Hitachi began looking for a steelmaking partner.\textsuperscript{17} Pacific Metals, a Japanese stainless steel company in those days, joined the project, and a pilot caster was built at Hachinohe, which became operational in 1994, with its experiences with strip casting from its partneship with Bethlehem Steel, Armco and Weirton (1986), and an electro-magnetic edge containment system it had defined its objective towards merely obtaining the ‘educate customer’ when purchasing future commercial casting projects.\textsuperscript{1} The US steelmaker Inland Steel became involved around 1994, with its experiences with strip casting from its partnership with Bethlehem Steel, Armco and Weirton (1986), and an electro-magnetic edge containment system it developed in the 1980’s.\textsuperscript{1,15} An agreement was signed between Hitachi and Inland Steel to test the electro-magnetic edge dams on the Hachinohe pilot caster and promising results were obtained by 1998.\textsuperscript{32} Despite successful trials, the project faded out of public view in the early 2000’s.
5. Strip Casting Projects in the New Millennium

5.1. The Eurostrip Process (Joint European R&D Effort) – Twin-roll Casting

During the last few years of the second millennium, frequent mergers and industrial synergies in the steel industry had had a profound impact on the development of strip casting technology. One such example is the formation of the joint European strip casting R&D project, the Eurostrip process.26)

The Italian steel firm AST continued to develop strip casting technology after its takeover in 1994 by the German steelmaker Krupp while the Myosos project was halted temporarily in 1998.25) In September 1999, the two initiatives were formally merged into one project, bringing together the experiences of VAI, ThyssenKrupp (with AST and CSM) and Usinor-Sacilor (later merged into Arcelor in 2001 and ArcelorMittal in 2006, parent of IRSID) in one new project called Eurostrip.27,35) VAI also became the exclusive plant builder for the Eurostrip project.28)

The newly established joint stainless steel producer under ThyssenKrupp, Krupp Thyssen Nirosta, gained interest in the Terni strip caster built by AST.27) The partners decided in December 1998 to build the pre-industrial scale twin-roll strip caster at the KTN’s Krefeld stainless steel plant in Germany instead of at AST’s Terni facility in Italy.29)

The Krefeld caster became operational in December 1999 with an annual production capacity of 100 000 ton, producing 304 stainless steel strips with 1.4–4.5 mm thickness and 1.430 mm width.27,35–37) In June 2001, an inline four-high hot rolling stand and an inline inductive heater were added to the caster.30) This caster was upgraded to full industrial scale producing at 400 000 ton/yr capacity in 2003.31) The schematic of the pre-industrial scale caster at Krefeld is shown in Fig. 5.

The Terni caster received significant upgrades since the merger as well. An inline four-high hot rolling stand was added in 2000, and by 2002 the Terni caster was able to cast 60t ladles and strips 1.130 mm wide, and receive up to 40% thickness reduction in hot-rolling.32)

In 2000, the Eurostrip research team predicted that the potential demand for carbon and silicon steel from strip casting would exceed that of stainless steel by 2003, and reach 2.75 Mt/yr by 2008.33) Therefore, the team dedicated the smaller Terni strip caster to strip casting of carbon steels, including electrical silicon steel as well as low carbon steel.34,35) The layout of the Terni strip caster is shown in Fig. 6 below. The studies of the fundamentals of strip casting were carried out using the lab-scale caster at the Aachen Institute of Technology (RWTH) in Germany, and an additional lab-scale caster was operated at IRSID (Arcelor Research) for specific tests and trials.35,36)

In early 2003, the installation of the double coiler system to the caster at Krefeld was completed. With the caster’s annual production capacity reaching 500 000 tonnes, the commercial operation of the strip caster for stainless steel was on the agenda. At the Terni facility, technical refinement for the production of thin and wide hot bands for carbon steel was underway.39)

The Eurostrip casters used the largest casting rolls among the several industrialized TRC processes; both the Terni and the Krefeld casters had rolls of 1 500 mm diameter. Eurostrip was one of the few industrialized strip casting processes available at the time.51 In 2003, ThyssenKrupp announced plans to establish a commercial strip casting plant for the production stainless steel strips in Pudong, Shanghai, cooperating with the Chinese steelmaker, Baosteel. However, the plan did not materialize due to problems with the plant’s location, as Expo 2010 was to take place nearby, and the construction of a steel mill was not permitted.40)

Since 2003, the Eurostrip consortium had become extremely cautious in developing its strip casting process, and has since been reluctant to release any information regarding the progress of the project. However, Corus said that the Eurostrip project was lagging behind the other two TRC initiatives (Castrip and Nippon Steel) and ‘will probably never reach commercial viability’.41) Very little information related to the Eurostrip process was available after 2003, leading to suspicion that the project was terminated sometime in the mid 2000’s for unknown reasons.

5.2. Horizontal Single-belt Strip Casting (HSBC) Project (BHP, McGill and Hazelett)

Besides twin-roll strip casting, the Horizontal Single Belt Casting (HSBC) process, independently conceived by Herbertson and Guthrie42) and Reichelt, Schwerdtfeger et al.,43) offers good strip properties through subsequent in-line hot-rolling with high productivity for steel strips.44) This process is similar in concept to the Pilkington float glass process for the production of glass sheet, where molten glass is continuously poured over a bath of molten tin on which it moves and solidifies into a long, continuous glass strip.45) The new plant, BHP (Australia), McGill University (Canada) and Hazelett Strip Casting Corporation (US) began an international collaboration in 1987 to develop an industrial HSBC process.45)

In 1989, Hazelett provided the consortium with a pilot-scale HSBC caster, which successfully operated at BHP’s Clayton Research Laboratories, Newcastle, Australia, and produced 7 mm thick, low carbon steel, at a casting speed of 24 m/min on the 2.6 m long, water-cooled, endless belt.46,47) A photo of the HSBC caster in action is shown in Fig. 7.

The project continued to progress until 1995, when BHP shifted its focus to the ongoing TRC project, which was in a more advanced state of development. The TRC project involved formal collaboration with Ishikawajima-Harima Heavy Industries (IHI, Japan). BHP subsequently withdrew from the HSBC project.45) In 1997, the pilot-scale caster was turned over to Dr. Guthrie and installed in the McGill Metals Processing Center (MMPC), Montreal, Canada, where McGill and Hazelett have continued to study and develop the process.49)
The caster received substantial upgrades after its return to North America, and now features a redesigned metal delivery system, and a unique in-line pinch roll/mini-mill designed by Hazelett, together with advanced control systems.45,50) Currently, the caster is used extensively in the studies of the effects of metal delivery system, belt substrate coatings, casting speed, melt superheat and substrate topography, on heat fluxes, microstructures, and the surface quality of metal/alloy strips. Sheet product characteristics, together with in-line thermo-mechanical treatments, as well as the strip casting possibilities of a wide variety of alloy systems, ranging from copper alloys, low carbon steel, ferroalloys and lower melting range alloy systems based on crystalline metals such as aluminum, magnesium, and bulk amorphous alloys, have been studied.45,46,50–52) The design schematic of the McGill-Hazelett HSBC caster and a picture of the in-line pinch roll/mini-mill system are shown in Fig. 8.53)

5.3. Belt Casting Technology (BCT) (Sweden, Finland and Germany)

The BCT process (formally known as direct strip casting, or the DSC process) is similar in principle to the HSBC process. Mannesmann Demag Metallurgy (MDM, now SMS Siemag AG)’s R&D of BCT technology began in 1986. In 1988; a pilot caster was commissioned in Belo Horizonte, Brazil, that cast carbon steel strips, 450 mm wide and 5–10 mm thick.15,44) Around the same time, an ECSC-funded study about the possibility of BCT casting was undertaken by the “Institut für Allgemeine Metallurgie” of the Technical University of Clausthal (TU Clausthal). This lead to the construction of a hot-model capable of producing 170 mm wide, 10 mm thick steel strips.15) The first casting trials of both projects were performed by 1989.44)

The Swedish Research Institute MEFOS in Luleå, began its strip casting research in the late 1980’s with the support of a consortium of Nordic steel companies. It received partial funding from both the Swedish and Finnish governments.54) After one year of preliminary study, MEFOS also chose the single-belt casting technology (BCT), and the

![Fig. 7. The Hazelett HSBC caster operating at BHP’s laboratory in Australia.](image)

![Fig. 8. Design schematic of the McGill-Hazelett pilot-scale HSBC caster (top) and the picture of the caster and its in-line pinch roll/mini-mill system (bottom).](image)
A co-operation agreement between MEFOS and MDM was signed in July 1991, in order to combine their R&D efforts. MDM moved its Brazil casting facility to MEFOS the same year. The project was also enlarged to include Daido Steel (Japan) and Vitcovice Steel (Czech Republic). The first casting trial at the MEFOS facility took place in December 1992 with a 450 mm wide, 5–10 mm thick, producing steel strips at 20–60 m/min. The basic design of a horizontal single belt caster proposed by MEFOS is shown in Fig. 9.

Various grades of steels were cast at MEFOS in the early 1990’s, including plain carbon steels and 18-8-stainless steels. Two different metal delivery systems, the low pressure system (LPS) and the tube feed system (TFS), were also investigated, as shown in Fig. 10. In 1995, after Sweden’s entry into the European Communities, the development of BCT at MEFOS received several phases of sponsorship from the ECSC. The first ECSC project (1995–1996)’s research activities was led by both TU Clausthal and MEFOS, during which MEFOS successfully demonstrated the high productivity and casting speed achievable by BCT. Clausthal performed material investigations, as well as casting and subsequent in-line rolling, and Salzgitter AG began cooperative research with Clausthal in 1995.

The second ECSC project ran from 1997–1998. At MEFOS, the caster performance was further improved and 900 mm wide strips were successfully produced. The goal for Clausthal was to further investigate materials and in-line rolling. Three different grades of steels have been cast successfully; austenitic stainless, low- and medium-carbon steels.

The third ECSC project took place between 1998 and 1999, with the objective of obtaining dimensioning data for the demo-caster, as well as trials at both MEFOS and Clausthal. MEFOS was also charged with emphasizing R&D on the feeding system, heat transfer, edge improvements and strip thickness control. The parallel project at Clausthal received sponsorship from German firms including Salzgitter AG and ThyssenKrupp. Research focused on the castability of carbon steel. By 2006, there were three pilot casters operational and the process is now progressing towards commercialization.

In September 2010, SMS Siemag announced that they had received a contract from Salzgitter AG to construct an industrial-scale BCT pilot plant. The plant is designed for 25,000 ton/year production capacity, the majority of which will be for Advanced High Strength Steels (AHSS, or High Strength and Ductility steels, HSD® steels). The plant is located in Peine, Germany, and is scheduled to be ready for commissioning in 2012. The project has received EU€ 19 million of sponsorship from the German federal government for its environmental friendliness.

5.4. Nippon Steel Corporation and Mitsubishi Heavy Industries (Japan) – Twin-roll Casting

The Japanese machine maker Mitsubishi Heavy Industries (MHI) began fundamental twin-roll strip casting tests in the early 1980’s. In 1985, a test caster, with 600 mm long 600 mm diameter rolls, was commissioned, and established the stable castability of 600 mm wide strips. Mitsubishi Heavy Industries began its collaboration with the Japanese steelmaker Nippon Steel in 1985 to develop a twin-roll strip caster for stainless steel. A 1-ton, 800 mm wide, lab-scale model was built in 1986 at Nippon Steel’s Yawata plant. This was upgraded to a 10-ton pilot caster in 1989 at Nippon Steel’s Hikari Works. A schematic of the Hikari pilot caster is shown in Fig. 13. The pilot caster became operational in
1989 using 800 mm wide, 1,200 mm diameter rolls. It was further upgraded in 1991 and 1,330 mm wide rolls were installed.2,3,9,60 The pilot caster was able to produce 1.6–5.0 mm thick steel strips at 20–130 m/min casting speed.34)

By 1993, the pilot plant was fully operational and the steel strips produced demonstrated tensile strengths and elongations equivalent to conventionally-produced steel strips, as well as exhibiting lower anisotropy and superior corrosion resistance.60) The partners announced that both an economic feasibility study and the construction of an industrial-scale caster would commence. The construction of the world’s first commercial TRC strip caster began in January 1996. The construction took 20 months and casting trials began in October 1997. Commercial production started one year later, in September 1998.34)

The Hikari caster was designed for austenitic stainless steel, its production capacity reached 20,000 ton/month in 1998 and had increased to 35,000 ton/month by 2002. Stainless steel strips were sold on the market since October 1998.1,5,59) The caster operated with 60-ton heats and had a pair of casting rolls 1,330 mm wide, 1,200 mm in diameter. 2–5 mm thick stainless steel strips were cast at up to 90 m/min and hot-rolled with an in-line, four-high, hot rolling stand.59) A schematic of the Nippon Steel-MHI strip caster is shown in Fig. 14.

In November 2002, Nippon Steel announced that the Hikari caster had achieved its productivity goal (300 ton cast in a five heat sequence), as well as strip quality. With plant annual productivity as high as 420,000 ton/yr, the Hikari caster was certainly the furthest-developed strip casting process at the time.53) However, Nippon Steel terminated the commercial operation of the strip caster at Hikari Works in September 2003. Reasons cited were that Nippon Steel’s cooperation with Sumitomo Metal Industries (SMI) had eliminated the need for a commercial strip caster, and that the 11 billion JPY (110 million US$) strip caster had never reached over 50% of its design production capacity, since its initial commissioning in 1998.62)

5.5. The Castrip Process: Nucor Steel (US), BHP (Australia) and IHI (Japan) – Twin-roll Casting

Ishikawajima-Harima Heavy Industries (IHI) began its investigation of twin-roll strip casting technology for stainless and carbon steels in 1982.63) The predecessor of the Castrip project began in 1989 as a joint venture between Broken Hill Proprietary Company (BHP) and IHI under the name ‘Project M’.64,65) Throughout the 1980s, the companies engaged in lab-scale research and a 5-tonne pilot caster was constructed at Unanderra, Australia, in 1990.1,66)

By 1991, 304 stainless steel strips with commercially acceptable quality were produced.64,67) The original focus of the Castrip project was to produce 304-grade stainless steel strips between 2 and 3.5 mm thick, but this was changed in the 1990’s to the production of low-carbon steel strips for the construction industry. A series of 1,300 mm wide low carbon heats were successfully cast in 1992.64) In 1993, 5-tonne steel coils of 2 mm thick and 1,300 mm wide strips were successfully produced.65,66) The basic schematic and components of the Castrip strip caster are shown in Fig. 15.

In August 1993, the construction of a full-scale strip cast-
The pilot-scale twin-roll caster at Corus Research, Development and Technology’s (Corus RD&T, now part of Tata Steel), Teesside Technology Centre (TTC), originally used in British Steel’s TRC project, was used to test and verify various aspects of the design concepts and modeling works of the MAINSTRIP project. It was reported in 2005 that a twin-roll cast strip from this pilot-caster was directly processed into hollow sections without intermediate rolling, and the product successfully achieved commercial standards requirements.

The MAINSTRIP process emphasizes the modular production plant concept, and had developed many unique patents and designs for the TRC strip casting process, such as movable casting heads, a unique ball-type submerged entry nozzle (SEN), recuperable and oscillating side dams, etc., which will be introduced later in this paper.

Despite successful tests, the MAINSTRIP process has yet to reach an industrial-scale testing phase, although it was reported that several Asian steel plants, particularly in China, have shown serious interest in the process. The schematic of a MAINSTRIP twin-roll caster is shown in Fig. 17.

5.7. Pohang Iron and Steel Co. (POSCO, South Korea) – Twin-roll Casting

POSCO began working on twin-roll strip casting in 1989 with the Research Institute of Industrial Science and Technology (RIST). The objective for POSCO’s project is to develop an industrial-scale strip caster for stainless steel in order to save on capital investment. Davy Int. from UK was responsible for designing a lab-scale model, and a pilot caster was built in 1994. The pilot caster became operational in 1995, with a casting capacity of 10-ton, using rolls 1 250 mm in diameter and 1 300 mm wide. Casting speeds are between 50–130 m/min and strip thickness ranges from 1.8–5.5 mm.

Through subsequent upgrades, the capacity was increased to 50-ton by the early 2000’s. Construction of a 600 000 ton/year industrial-scale, demonstrative caster (designated poStrip) began in June 2004 at Pohang Works and was completed in June 2006. Semi-commercial production began in July 2007. The overview of POSCO’s commercial-scale twin-roll strip caster is shown in Fig. 18. In March 2007, poStrip had successfully cast 1.5 mm thick, 304 stainless steel strips. Subsequently, four more stainless steel grades were successfully cast. POSCO plans to install the No. 2 in-line rolling mill by the end of 2011, in order to enable the production of 1.3 mm thick TRC strips.

5.8. Shanghai Baosteel Group Corp. (China) – Twin-roll Casting

Baosteel began its feasibility studies on strip casting in 2005. A 1 250 mm wide, 20-ton twin-roll unit was installed in December 2006. The pilot-caster was equipped with movable casting heads and a SEN (submerged entry nozzle). The twin-roll unit achieved an average casting speed of 70 m/min in November 2007, with a strip thickness of 2.0 mm. A 80-ton twin-roll caster with a nominal strip width of 1 300 mm, was commissioned in November 2007 with an average casting speed of 50 m/min.
the early 2000’s. Its TRC project was officially launched in November 2001, and the installation of the TRC caster began in October 2002.\textsuperscript{83} In 2004, Baosteel signed a collaboration agreement with Carnegie Mellon University, to further strengthen the research team.\textsuperscript{61,84} In 2003, a 1200 mm wide, twin-roll pilot caster was completed and commissioned. Trial casts for stainless steel, carbon steel and silicon steel were successfully conducted in 2004, 2005 and 2006 respectively.\textsuperscript{83,85}

The second phase of development began in 2007, and by 2008 the pilot caster was upgraded and a four-roll, in-line, hot mill was installed and successfully tested. In February 2009, the full-scale test caster entered semi-commercial production. R&D work continued with focus placed on lowering production costs and improving surface quality.\textsuperscript{85} The Baostrip full-scale test caster has 800 mm diameter rolls and is capable of producing 2–5 mm thick, 1350 mm wide steel strips, at 110 m/min casting speed, as shown in Fig. 19. Baosteel is highly confident of the full commercialization of the Baostrip process in the near future.\textsuperscript{85}

\section*{5.9. Other R&D Efforts}

Besides the major projects described above, other strip casting projects running at lab-scale or pilot-scale TRC casters up till the early 2000’s are listed in Table 1.\textsuperscript{5,15,35,86}

\begin{table}[h]
\centering
\caption{List of some operational lab- and pilot-scale TRC strip casters as of early 2000’s.\textsuperscript{5,15,35,86}}
\begin{tabular}{|c|c|c|c|c|}
\hline
Company/Institution (country) & Casting speed (m/min) & Roll diameter (mm) & Strip thickness (mm) & Strip width (mm) & Steel grade \\
\hline
Kawasaki (Japan) & 60–420 & 550/800 & 0.2–0.8 & 500 & Stainless, Special \\
IFW Dresden (Germany) & 90–480 & 350/500 & 0.6–3 & 30–800 & Stainless, Special \\
Max Planck Inst. (Germany) & 5–25 & 330 & 0.5–3 & 120 & Carbon, Special \\
ITRI (Rep. Of China) & 12–24 & 400 & 2 & 300 & Stainless \\
VNIIMET-MASH (Russia) & 120–360 & 340 & 0.1–0.5 & 150–300 & Special \\
\hline
\end{tabular}
\end{table}

\section*{5.10. Summary}

The development of strip casting technology has come a long way since the 1980’s. There has been a substantial reduction in the number of institutions and firms involved in the development of steel strip casting. This has been due to natural attrition and/or industrial collaboration, cooperation, networking and mergers/take-overs. It also reflects the high level of financial investment and research commitment required for the successful commercialization of the process.\textsuperscript{2} As of 2009–2010, four TRC processes reached the industrial stage (Castrip, Eurostrip, Nippon Steel/MHI at Hikari, and poStrip), while one is in full-scale production.
testing at Baosteel. Of the commercialized operations, Castrip has focused on carbon steels and has used the high heat transfer roll technology developed by BHP in the 1990s, allowing the production of ultra-thin hot bands. Their choice of smaller casting rolls gave them the advantage over other competing technologies in terms of lowering operating costs, which was one of the most important reasons that the Castrip process could be successfully commercialized before other contemporary projects, such as Nippon Steel and Eurostrip.

Due to the rapid cooling experienced during strip casting, the as-cast strips tend to be stronger and less ductile. All commercialized TRC processes include considerable in-line post-casting processing to give their strips mechanical properties that are similar to conventionally produced strips. A comparison of the four commercialized strip casting processes is shown in Table 2. The data on currently operational HSBC casters are summarized in Table 3.

Major developments in strip casting technology since 1982 are summarized in Fig. 20.

6. Application Outlook for Strip Casting of Steel

Two types of steel mills dominate the production of steel strips today; integrated mills and mini-mills. They have drastically different characteristics, production philosophies, and marketing strategies. Any strip casting technology must be able to fill these if it is to be successfully commercialized.

Integrated mills are massive plants, with a production capacity 2–10 Mt/yr, performing all major operations involved in steel production; ironmaking, steelmaking, casting, roughing and finishing. These mills are oriented to big customers requiring high quality steel in large quantities. Their locations are chosen to optimize production and logistics, rather than to suit their customers. Currently, strip production by integrated mills is primarily carried out by CCC, producing as-cast slabs of ~200 mm thickness. These thick slabs go through numerous operations to be reduced to 3–20 mm thick strip. Repeated heating and rolling, correct inherent defects, and break down inclusions in the cast slab, so as to ultimately produce high quality strips for the market place. However, this process is highly labor intensive, machine intensive, and costly. The high capital cost means that it can only become profitable provided the production tonnage is over several million tons per annum.

Mini-mills are more recent creations that arose with the invention of mini-mills, using EAF’s to melt scrap and in-line melting, casting and rolling of steel billets. As the capacity of mini-mills increased, they sought to enter the more lucrative areas of steel strip production. Nucor, one of the large-tonnage mini-mill operations, dedicated to the remelting of steel scrap in North America, was a leader in bringing Thin Slab Casting (TSC) machines to produce steel sheets that are relatively competitive with those produced by the large integrated steel mills.

The first thin slab caster of its kind was built by Nucor in 1989 at Crawfordsville. A typical mini-mill has a production capacity of 0.5–2.0 Mt/yr. Unlike integrated mills, it primarily serves customers who are not in need of large tonnages or of high surface quality. TSC is capable of casting steel slabs as thin as 50 mm, but usually operates to produce thicker slabs (~60 mm) so as to maintain slab surface quality. Mini-mills do not engage in ironmaking, and their raw material comes primarily from recycling steel scrap and partially from direct reduced iron (DRI), which is melted in EAF’s, and subsequently cast using TSC processes. Logistics is a much more important factor in operating mini-mills than integrated mills. Mini-mills are expected to be most profitable when the supply of raw materials is located within a 200 km range, and customers are within a 500 km range.
It was reported in 2003 that more than half of the metallurgical equipment of large steelmakers, worldwide, had been in operation for over 25 years, and that replacement equipment is needed in the near future. This offers a unique opportunity for strip casting technologies, since it fits the production strategies of both types of steel mills.

For large integrated steel mills, the HSBC strip casting technology currently under development would be ideal. Unlike the TRC process, a commercialized HSBC caster has no mechanical factors limiting its productivity. Production capacity can be increased by simply lengthening the belt; a commercial HSBC caster with a cooling length of 12 meters, can be expected to reach an annual productivity of up to 2–2.5 Mt/m-width, easily capable of meeting the volumetric steel flow of integrated mills.

Since HSBC is a relatively simple process versus TRC, HSBC casters would require less capital investment and operating costs, versus the cost of several TRC casters needed to reach similar production capacities. Moreover, the higher potential productivity of the HSBC process also means lower specific capital costs (cost per ton/yr capacity) than TRC, making it a far more suitable choice for integrated mills with large production capacity.

Finally, due to the considerable size reduction from the in-line hot rolling in the HSBC process, most inherent casting defects in the steel casts can be corrected to give good strip quality. It was shown that for an HSBC steel cast, after in-line hot rolling entailing a 66% hot reduction, practically all porosities can be removed. Microstructurally, the downstream thermo-mechanical processing can break down the large austenitic grains in the as-cast steel (~400 μm) into 10- to 20 μm ferritic grains, giving the strip cast steel mechanical properties (primarily ultimate tensile strength and elongation) matching those of strips produced conventionally. This means that steel strips produced from HSBC could potentially meet the high quality requirements of integrated mill customers at a fraction of the cost.

On the other hand, both the HSBC and the TRC caster are ideally suited for mini-mills. Firstly, a TRC caster’s annual production capacity (~500 000 ton) closely fits the production scale of mini-mills (ranges from 500 000 to over a million ton). The productivity ratio of HSBC casters is also well-suited for larger mini-mill operations.

Furthermore, due to the lack of substantial size-reduction after casting, the sheet products of TRC casters will have lower surface quality than those produced by the HSBC process. As mentioned earlier, this is a significant issue for integrated mills with high quality requirements. For mini-mill customers with less strict demands for strip quality, TRC is more than capable of producing market-worthy strip products.

Additionally, both HSBC and TRC technologies enable the recycling of scrap metals containing higher impurity levels in EAFs. This offers a significant economic advantage to North American mini-mills which obtain most of their steel from recycled scrap, as mentioned in the previous sections.

In addition to replacing existing conventional continuous casters, the incorporation of either HSBC or TRC casters by integrated mills with excess steelmaking capacity could also be advantageous, since it would offer a cheap and efficient way of utilizing the excess capacity, and simultaneously increase the range of steel grades available, such as the high-manganese Advanced High Strength Steels (AHSS) that could be produced economically by the HSBC process.

As presented earlier, strip casting facilities require significantly shorter process-lines (60~150 m for TRC, ~100 m for HSBC), compared to both CCC and TSC (~600 m and ~370 m, respectively). The lower capital cost, compact production lines and production-flexibility of strip casters, can be expected to stimulate the establishment of a new type of steel mill, the micro-mill. The name ‘Micro-Mill™’ has already been officially registered for the type of steel plant utilizing strip casting technology.

A micro-mill is similar to mini-mills, in that it does not engage in iron-making or primary-steelmaking, but differs from mini-mills since it is based on strip casting (either HSBC or TRC) technologies rather than TSC. Micro-mills are expected to be able to produce strips with better quality, at comparable/lower costs than mini-mills with TSC casters. The high flexibility of the strip casting process will also enable micro-mills to meet individual customer demands more accurately, in terms of steel grade composition, batch sizes and delivery times.

Nucor’s Crawfordsville operation where the Castrip process was first implemented commercially can be considered as the world’s first TRC-based micro-mill. Nucor’s second micro-mill in Blytheville, Arkansas, was completed in January 2009. Salzgitter’s AHSS plant in Peine, Germany will be the world’s first HSBC-based micro-mill, expected to be commissioned in 2012. POSCO’s poStrip project and Baosteel’s Baostrip are advancing rapidly toward full commercialization. The conditions of Nippon Steel’s TRC project and Eurostrip are unknown and presumably have been terminated.

7. Conclusions

Strip casting technology has come a long way since its early conception in the 1840’s. As a result of intensive research and development efforts undertaken throughout the world since the 1980’s, several twin-roll casters have already been commercialized to much fanfare, but were quietly abandoned later on. Presently, only two TRC technologies are in full commercial operation (Castrip and poStrip), with several more under development (Baostrip, MAINSTRIP, etc.). The commercialization of Horizontal Single-Belt Casting (HSBC) or Belt Casting Technology (BCT) by Salzgitter, is expected to be realized in 2012, and could represent a step change for integrated steel mills.

In general, both strip casters offers an efficient, environmentally-friendly and economical approach to the production of hot strips. The HSBC technology is ideal for both integrated steel mills and mini-mills alike, while the TRC technology is well-suited for mini-mill operations. The commercialization of strip casting technologies may stimulate the establishment of a new type of steel mill: the micro-mill.

In light of these findings, it is highly probable that strip casting technology will be widely implemented globally in the coming decades, initiating a revolution in the way steel strips are made, delivering impacts no less than the invention of thin-slab casting technology over 20 years ago for the global steel industry.

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