Development and Commercialization of Twin Roll Strip Caster

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IHI started development of the strip caster in 1982, and successfully achieved continuous casting by a laboratory caster, which was then expanded to collaboration with BHP (currently BSL) of Australia in 1989. The pilot plant for 5-ton melt was constructed and succeeded in casting. Next, a commercial scale demonstration plant for 60-ton melt was built in 1994, which progressed well. For further development, Nucor of the USA joined with IHI and BSL in 2000 and established a joint corporation, Castrip LLC. The first commercial facility was constructed at the Crawfordsville Steel Works of Nucor and has produced 650 000 tons of low carbon steel strips as of 2007 since the start-up in 2002. Ultra thin Cast steel Strips (UCS, 0.85 to 1.5 mm thick) produced by the caster are now selling well in the market of those from the conventional hot/ cold strip rolling mills. IHI has received an order for a second commercial facility to be operated in early 2009. Furthermore, the strip caster has the potential to achieve the dream of competitiveness in producing value-added products that cannot be achieved by the conventional slab casting & rolling processes.

1. Introduction

A twin roll strip caster, invented by Sir Henry Bessemer in 1856, is a technology to directly cast molten steel into thin strips. In the 1980s, many Japanese and European steel makers & heavy industry manufacturers such as Nippon Steel Corporation and Usinor/Tyssen actively tried to develop this technology as the Near Net Shape Technology for stainless steel, while IHI tried to develop the technology mainly for carbon steel, and a few groups continued these efforts in the 1990s. $^{(1), (2), (3), (4)}$

IHI started laboratory casting experiments of twin roll strip caster in Oct. 1982, made several fundamental breakthroughs, started collaboration with BHP, Australia in 1989, and paved the way for the commercialization of strip casting for common steel for the first time in the world. In 2000, Nucor, a U.S. company, joined BHP and IHI, and the three organizations established a joint venture, Castrip LLC, and IHI received an order for the first commercial strip casting facility from Nucor. The first commercial facility was constructed at the Crawfordsville Steel Works of Nucor, Indiana in 2001, which started operations in 2002, and has so far produced 650 000 tons of low carbon strips as of 2007. The ultra thin cast steel strips (UCS) having a thickness of 0.85 to 1.5 mm have been going to replace hot and cold-rolled steel strips and have been widely put into practical use. IHI has received

an order for a second commercial facility from Nucor. This facility is being constructed in Blytheville, Arkansas and is scheduled to start its operation in early 2009. This paper describes the characteristics of twin roll strip casters comparing with slab & thin slab casters, the history of their development, the operation status of the first commercial facility, and the characteristics of steel strips produced by the facilities. ^{(5), (6)}

2. Principles and characteristics of twin roll strip caster

As shown in **Fig. 1**, a twin roll strip caster continuously produces strips by solidifying molten steel retained

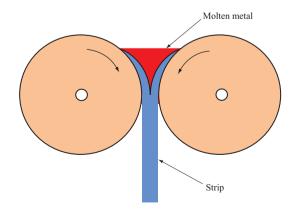


Fig. 1 Principle figure of twin roll strip caster

between rotating twin roll surfaces and attaching two solidified shells at the nip. Whereas in slab continuous casting, powder and lubricant are applied to the casting mold and the slab is gradually pulled out while the mold is being vibrated. So, the twin roll caster can make a thin strip in a shorter time without powder or a lubricant. As shown in **Table 1**, the basic casting parameters for twin roll casting differ greatly from those for slab continuous casting. The twin roll strip caster is characterized by its extremely short solidification time and significantly high heat flux. This production method enables high-speed production of thin strips, making it highly productive and attractive. However, it is technically difficult to control such short solidification time and overcome excessive

Table 1	Fundamental	casting	parameter
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Item	Unit	Strip caster	Thin slab caster	Thick Slab caster
Thickness	mm	1.6	50	220
Casting speed	m/min	80	6	2
Average heat flux	MW/m ²	14	2.5	1.0
Solidification time	s	0.15	45 ^{*1}	1 070*2
Average cooling rate	°C/s	1 700	50	12
			(Note) *1 :	K factor $= 29$



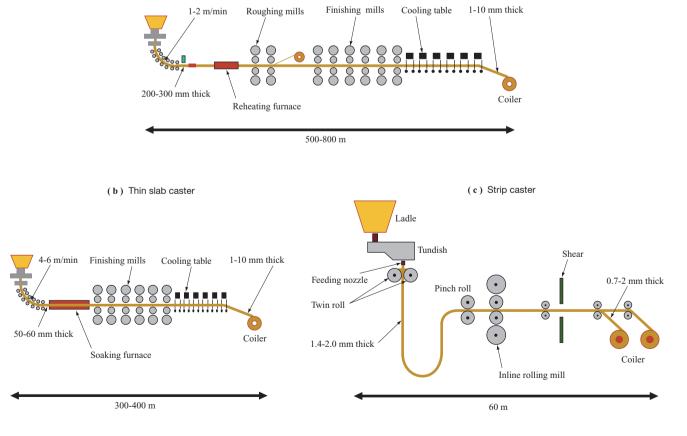
thermal load applied to the casting rolls. In recent years, however, advanced materials, basic research on initial solidification, high-speed computers, and industrial casting know-how have been combined to form the foundation of the commercializing technical innovations. The key papers on carbon steel strip casting in this 10-year breakthrough are listed as references in this paper. $^{(1), (2), (7), (8)}$

As shown in **Fig. 2**, comparison of slab caster, thin slab caster and strip caster, a strip caster does not require the installation of a heating furnace and multiple rolling mills, and the facilities length is only one-tenth of the conventional ones, therefore much saving on facilities costs and energy consumption is achieved. Because, as shown in **Table 2**, energy consumption and greenhouse gasses can be significantly reduced, a strip

 Table 2
 Comparison of energy consumption and carbon dioxide generation

Item	Energy consumption (GJ/t)	CO ₂ generation (t)	
Thick slab CC + HSM	1.80	0.20	
Thin slab CC + HSM	1.08	0.14	
Strip caster	0.20	0.04	

(Note) HSM : Hot Strip Mill



(a) Slab caster

Fig. 2 Schematic diagram of Slab caster, thin slab caster and strip caster

caster is an environmentally friendly facility that meets the needs of the age.

3. History of the development and establishment of Castrip LLC

After IHI started the development of twin roll strip casters in 1982, it made several breakthroughs to achieve continuous casting and produced carbon steel and stainless steel strips having a width of 200 mm \times 100 kg melt and 400 mm \times 1 ton (**Fig. 3**). It started a joint research with BHP, Australia (currently BSL) in 1989 and produced stainless steel and low carbon steel strips at a 5 ton pilot plant having a width of 1 300 mm at BHP Unandella Steel Works (**Fig. 4**). In 1995, the commercial scale demonstration plant equipped with a 60 ton electric furnace was constructed at the Port Kembla Steel Works of BHP (**Fig. 5**). This facility had cast 34 000 tons of low carbon steel by 1999 and

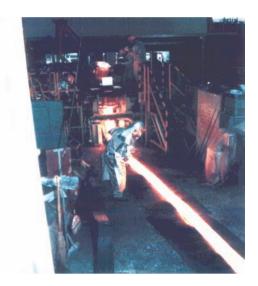


Fig. 3 Strip casting experiment at IHI

produced inline-rolled coils such as 1 mm thick (**Fig. 6**), used as roof materials, and they had then paved the way for commercialization. In 2000, Nucor, a U.S. company, joined IHI and BHP, and they established a joint venture, Castrip LLC, for the purpose of selling the license of strip casters and decided to construct the first commercial facility at the Crawfordsville Steel Works of Nucor. Coincidentally, the same steelworks had also started the world's first commercial thin slab caster, before the history of commercial twin roll strip casters.

4. Development with the commercial scale demonstration plant of IHI and BHP

Figure 7 shows a schematic diagram and specifications of the commercial scale demonstration plant. Because this plant was designed for producing carbon steel thin strips with a thickness of 2 mm or less, the casting roll had an extremely small diameter of 500 mm, compared



Fig. 4 Pilot plant at BHP



Fig. 5 Commercial scale demonstration plant at BHP

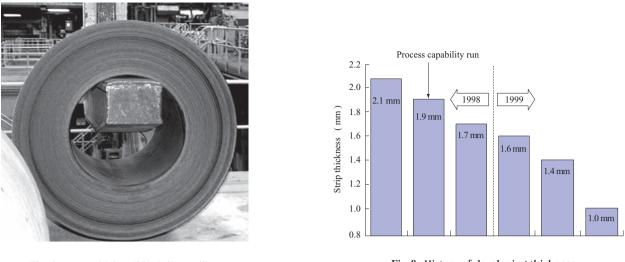


Fig. 6 1 mm thick coil by inline rolling

Fig. 8 History of developing thickness

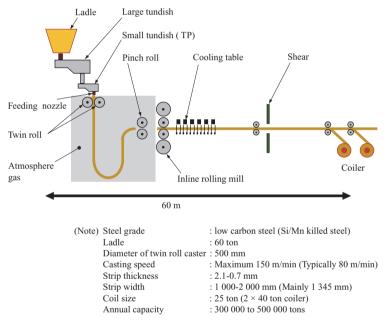


Fig. 7 Schematic diagram and specification of commercial scale size development plant

with those of other companies. Therefore, this casting roll is lightweight and cost-effective, and has achieved high-speed control response, and the rolls can easily be replaced. Moreover, the smaller side dam can reduce the running costs and is advantageous in respect of controllability. The method does not require dummy bars, facilitating the start and stop operations. For the 4-high rolling mill, the rolling load is 3 000 tons, and it is equipped with an automatic gauge controller. Strips are cooled at the subsequent run-out table, and coils are continuously produced by the drum shear and two coilers. Figure 8 shows the history of the development with silicon-killed low carbon steel cast by this plant. With a cast strip thickness of 1.9 mm, process capability run (reproducibility test) was conducted 29 times under the same conditions, by full casting the

ladle every time the test was conducted, to verify the operating reliability. Furthermore, when thin strips 1.4 mm thick were cast at 80 m/min., the thickness of a coil was reduced to 1 mm by inline-rolling it. Figure 9 shows the excellent edge shape of a coil produced by this plant. Figure 10 shows that the strip thickness accuracy of the as-cast strip is equivalent to that of the conventional hot-rolled strips. The oxidized scale thickness of the as-cast strip was about 6 µm, equivalent to that of the conventional hot-rolled strip. Figure 11 shows that the crystal grain becomes finer as the inline reduction rate increases. As shown in Table 3, the mechanical characteristics can be adjusted by changing the casting speed and reduction rate. As shown in Fig. 12, both high-strength materials and low-stress yield but high-elongation materials can be produced



Fig. 9 Edge of coil produced by development facility

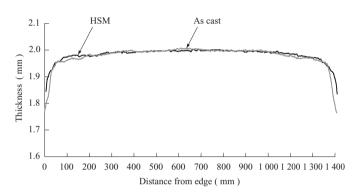


Fig. 10 Thickness distribution of as cast strip and conventional strip by hot strip mill

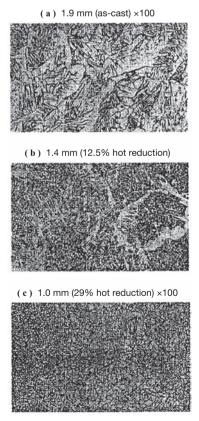


Fig. 11 Rolling rate and grain size

Table 3 Mechanical properties

Item	Unit	Strip casting			Hot strip mill	
Casting speed	m/min	45	80	80	80	-
Cast thick	mm	1.9	1.6	1.6	1.4	_
Inline reduction	%	0	0	13	29	_
Final thick	mm	1.9	1.6	1.4	1	2
Rolling temp	°C	_	_	1 050	1 050	1 200 to 850
σ_{y}	MPa	280	300	300	320	250 to 360
$\sigma_{ m b}$	MPa	420	440	440	450	320 to 440
Elongation	%	28	26	26	28	22 to 35

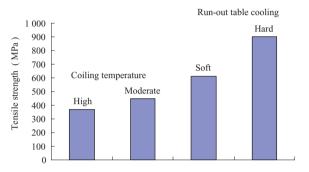


Fig. 12 Various property materials by changing of cooling condition of run-out table and coiling temperature

with the same chemical composition by adjusting the cooling conditions at the run-out table and the coiling temperature. When molten steel containing 0.4% of Cu and 0.2% of Sn was cast, no cracks were observed, although the Cu and Sn contents significantly exceeded the usual standard values and, with the conventional hot rolled materials, casting such molten steel is strictly restricted because grain boundary cracks are more likely to occur. This is thought to be because, with strip casters, rapid cooling and solidification prevents Cu and Sn from precipitating. Because it is expected that the contents of Cu and Sn in scrap will be increased, strip casting will be more advantageous than the conventional processes. Cu provides steel with high strength and weather resistance. As shown in Fig. 13, it can be expected that compared with the conventional production methods, a much wider variety of steel strips will be able to be produced with the same composition by using impurities considered harmful. Figures 14 and 15 show examples of strips that have been coldrolled, plated, roll-formed, and processed into building materials and furniture products. Figures 16 and 17 show the as-cast strips processed into drums and seamwelded pipes, whose weldability has been verified as being satisfactory.

5. First commercial strip caster installed at Nucor

The commercial scale demonstration plant installed in BHP was relocated to the Crawfordsville Steel Works of

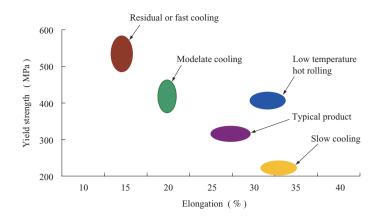


Fig. 13 Various properties from single chemistry and addition of "harmful" elements

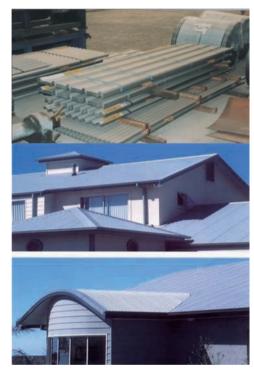


Fig. 14 Construction materials and roof made from strip casting materials



Fig. 15 Table and chair made from strip casting materials



Fig. 16 Drum can made from as-cast strip



Fig. 17 Electric welded pipes made from as-cast strip

Nucor with modifications, and the construction of the first commercial facility licensed by Castrip LLC began in February 2001. **Figure 18** shows the appearance of the CASTRIP[®] plant.

Figure 19 shows the CASTRIP[®] facility (strip casting facility licensed by Castrip LLC). The size of the ladle is 110 tons. The ladle and tundish are shared with the existing thin slab caster. The electric furnace



Fig. 18 NUCOR Crawfordsville CASTRIP® workshop

facility is located 250m away; therefore, molten steel is transported to the CASTRIP[®] facility by a truck. The main casting facilities are equipped with a vacuum tank degasser (VTD), which was installed by Nucor's initiative to solve a quality problem of hydrogen and nitrogen, and ladle metallurgy furnace (LMF) as steelmaking adjustment facilities. Both facilities are located inside the CASTRIP® facility, and adjust the composition and the temperature of molten steel fed to the caster. The tundish is set immediately above the small tundish ("Transition Piece" or "TP"). The TP can reduce ferro static pressure in molten steel and helps distribute molten steel evenly in the direction of the casting roll width. The core nozzle located between the twin rolls receives molten steel from the TP and immerses itself in the molten steel pool. The casting speed is normally from 50 to 100 m/min., and the strip thickness is from 1.1 to 2.0 mm. The inline rolling mill has reduction capacity of 50%, although it is normally operated with reduction of 30% or less. Produced coils will be cooled for 24 to 48 hours before undergoing the finishing process or being delivered to the customer. Table 4 shows the facility specifications.

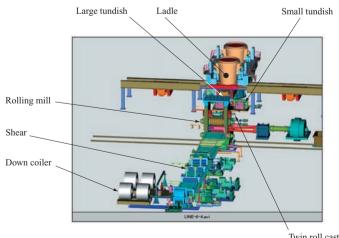
Figure 20 shows the exchange of ladles during continuous casting. In the figure, an empty ladle is being

Table 4 Specifications of NUCOR Crawfordsville CASTRIP®

Item	Unit	Specification
Heat/Ladle size	t	110
Caster type	mm	ø500 twin roll
Casting speed	m/min	80 (typical) 150 (maximum)
Product thickness	mm	0.7 to 2.0
Product width	mm	1 345 maximum
Coil size	t	25
Inline rolling mill	_	Single stand – 4 High with Hydraulic AGC
Work roll dimensions	mm	475 × 2 050
Back-up roll dimensions	mm	1 550 × 2 050
Rolling force	MN	30 maximum
Main drive	kW	3 500
Cooling table	_	10 top and bottom headers
Coiler size	t	2×40 coilers
Coiler mandrel	mm	<i>ф</i> 760
Annual capacity	t/y	500 000 maximum



Fig. 20 Ladle exchange during casting at the CASTRIP[®] plant at Nucor Crawfordsville



Twin roll caster

Fig. 19 CASTRIP[®] (Commercial strip casting facility) of Nucor Crawfordsville

turned and moved out of the line, to the upper right, and another ladle filled with molten steel is about to be set in the casting position.

The CASTRIP[®] facility constructed at the Crawfordsville Steel Works started operations in May 2002. And since then it has been improved in respect of casting and operations to meet the demands in various markets. As a result, its production volume reached 650 000 tons as of the end of 2007. Currently, the 3 ladles sequence casting operation is being performed to meet the demands for increased production. In December 2007, it broke the record for the longest sequence casting operation three times, which is 24 ladles, 38 hours, 2 467 tons and then shipped 2 387 tons of coils.

The manufacturing method of ultra thin cast strips (UCS) produced by CASTRIP[®] differs from those of the conventional hot-rolled and cold-rolled strips; therefore, in September 2004, a new standard "A1039/A1039M-04" for strips produced by the twin roll casting process was obtained from ASTM (American Society for Testing and Materials), in order to have the strips recognized by the markets. **Figure 21** shows the whole gauge and grade ranges of the products recently produced by the CASTRIP[®] process. ⁽⁶⁾ As noted in the graph, the minimum thickness of the hot rolling materials is 0.05 inches (1.27 mm). Normally, thinner materials are supplied as cold-rolled strips. In the figure, A, B, C, D and E indicate the product application shown below.

A : Steel framing and structural deck

0.035 to 0.04 inches thick. Normally, strips used for these materials are cold-rolled before they are galvanized; however, in the CASTRIP[®] process, they are supplied without being cold-rolled.

B : Racking and framing

0.043 to 0.046 inches thick. UCS, used as a substitute for high strength cold-rolled carbon steel, has higher weldability as a rack part.

C: Steel framing

Grade (strength) 50, 0.043 to 0.055 inches thick.

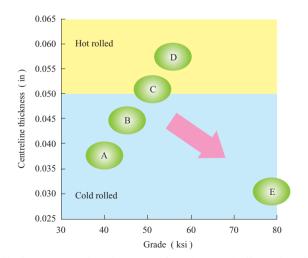


Fig. 21 Gauge and grade ranges of products typically produced via the CASTRIP[®] process

Higher strength products have been required owing to the increasing demand for frame materials for construction use, and strips in this application range can meet such a requirement. They may be galvanized.

D : Structural purlins and racking

0.055 to 0.06 inches thick. Strips used for both structural purlins and rack materials have a yield stress of 55 ksi (380 MPa) or more, and provide medium level formability.

E : Steel framing

A light rolled cold-rolled strip UCS, has elongation of more than 10%, Grade 80. Strips in this application range have excellent performance as residential steel framing for housing.

IHI has been closely cooperating with the people of Castrip, BSL and Nucor, on a wide range of efforts such as important designing of caster, engineering analyses of caster & mill line by mathematical heat/flow/dynamic & water simulations, metallurgical studies such as development of new UCS material and further study of solidification.⁽⁹⁾

6. Conclusion

IHI in 1982 launched the development of a twin roll strip caster, an idea that was already about 150 years old at the time, and made fundamental breakthroughs; jointly with BHP (currently, BSL) developed it by the Pilot Plant and the Commercial Scale Demonstration Plant; established Castrip LLC, a joint venture, with BHP and Nucor; and successfully produced commercial facilities capable of supplying products to the market. The CASTRIP[®] facility constructed at the Crawfordsville Steel Works has so far produced 650 000 tons of ultra thin cast strips (UCS) made of low carbon steel. The properties of UCS products are almost equal to those of low carbon strips produced by the conventional hot rolling processes. The recent casting strategies at the Crawfordsville Steel Works are focused on expanding the applications of products. At the same time, the second CASTRIP® facility of Nucor is being constructed in Blytheville, Arkansas. UCS products, whose process routes are unique, have a potential to produce value-added products that cannot be produced by the conventional rolling processes. In order to fulfill the potential of the CASTRIP® process, Castrip has started to develop the technology to cast new grades of strips.

IHI has an exclusive license to manufacture CASTRIP[®] facilities, which are capable of producing energy-saving Near Net Shape Products, and can, unlike large mills with blast furnaces, be installed in a limited space and with a lower initial investment. IHI believes that this environmentally friendly facility will become widely used throughout the world.

Finally, the authors would like to express their great gratitude to Castrip, BSL, Nucor and the IHI Corporate Research & Development, also all senior staff members who have already retired for their great contribution to the development of strip casters.

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