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RECENT PROGRESS ON COMMERCIALIZATION OF CASTRIP® DIRECT STRIP CASTING TECHNOLOGY AT NUCOR CRAWFORDSVILLE

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The world's first commercial installation for direct casting of low-carbon steel sheet utilizing CASTRIP® technology is undergoing production ramp-up at Nucor Steel's plant in Crawfordsville, Indiana. Construction of the plant was initiated in February 2001 and the first ladle was delivered to the caster in May 2002. Since that time, Nucor Steel has been working with technology partners BlueScope Steel (formerly BHP Steel) and IHI (Ishikawajima-Harima Heavy Industries) to fully commercialize this exciting new technology for the direct production of steel sheet less than 2 mm in thickness.
Key words: *strip casting, twin-roll casting, CASTRIP technology, hot rolled steel, thin-gauge hot rolled.*

The CASTRIP process was jointly developed by BlueScope Steel and IHI beginning in 1989, under the code name Project M. Following lab-scale research through the 1980s, the companies agreed to collaborate on a larger scale project; at first a pilot plant, then a full-scale development plant. The original focus for the joint project was the casting of stainless steel (Grade 304) sheet between 2 and 3.5 mm. However, during the mid 1990s, Project M turned its focus to the direct casting of low-carbon steels for the construction industry. BlueScope Steel is Australia's premier flat rolled steelmaker and a significant portion of its output is directed to construction markets. After more than a decade of successful development and the production of more than 30000 tons of strip, BlueScope and IHI agreed that the technology was ready for full commercialization. Thus in late 1999, Nucor Steel joined the effort and built a full commercial plant at Crawfordsville. (The Crawfordsville plant is noteworthy as it is also the site of the world's first thin-slab casting plant, commissioned in 1989.) Construction of the new facility was initiated in late February 2001. Following 14 months of construction and cold commissioning, the first ladle was delivered to the CASTRIP facility on May 3, 2002. Since that time, the plant has steadily made progress towards full commercial production of Ultra-thin Cast Strip (UCS). Further information on the history and development of CASTRIP technology is available in the litereature [1–4].

The CASTRIP process, similar to all twin-roll casting operations, utilizes two counter-rotating rolls to form two individual shells that are formed into a continuous sheet at the roll nip. A simple schematic in Fig. 1 indicates liquid metal, rolls, and the solid sheet. Although the concept of casting a continuous sheet in this manner was developed some 150 years ago by Sir Henry Bessemer, it is only in the past decade or so that availability of high speed computing, advanced materials, fundamentals of early solidification and industrial casting know-how have been combined to provide the basis for a com-

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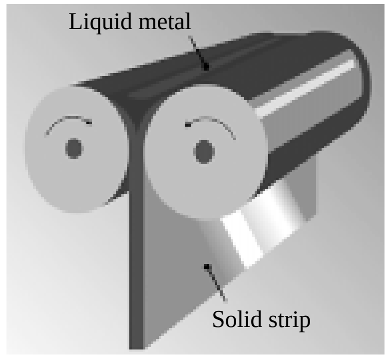

Fig. 1. Simple schematic of twin-roll casting.

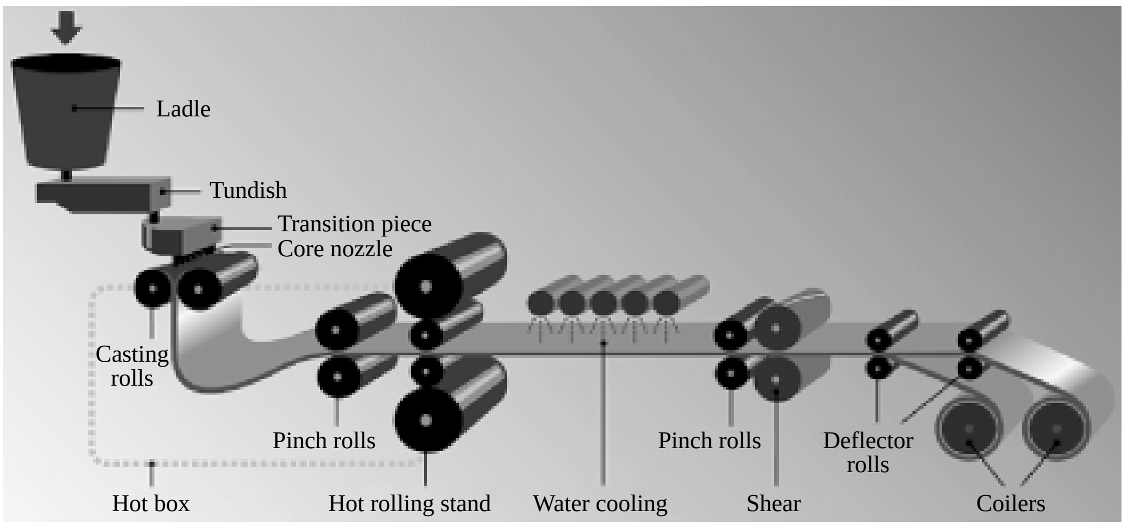

Fig. 2. Main components of the CASTRIP process.

mercial technology in the steel industry. Not indicated in Fig. 1 are the refractory side dam pieces that are positioned against the casting rolls at either end. These pieces are used to contain the melt pool.

The main components of the CASTRIP facility at Nucor Crawfordsville are depicted in Fig. 2. As can be seen, the process begins with a ladle of steel above a tundish. In the case of the Crawfordsville facility, the ladle size is 110 tons and both ladle and tundish are identical to those employed by Nucor at their thin-slab casting plant. The existing EAF shop, some 500 meters away, provides steel to the CASTRIP facility via a rubber-tired carrier. In addition to the main casting components, an LMF station located within the CASTRIP plant trims composition and temperature to final casting requirements. Referring to Fig. 2, the tundish is located directly above a smaller tundish or transition piece that is designed to reduce the head of the liquid steel as well as distribute metal flow across the barrel length of the casting rolls. The core nozzle receives streams of liquid steel from the transition piece and sits between the casting rolls, immersed in the melt pool. As casting proceeds and the liquid steel is transformed into a solid sheet, it exits downwards forming a free loop below the casting rolls. The speed of casting is roughly 80 m/min and the thickness of the solid strip is typically 1.6 mm or less. In order to limit scale formation on the strip surface, a protective atmosphere is maintained through the use of a “hot box” which contains the strip until entry into the hot rolling stand. Pinch rolls, located just before the stand as well as further down the run-out table, maintain tension on the strip. The in-line hot rolling stand is capable of as much as 50% reduction to the sheet; however, typ-

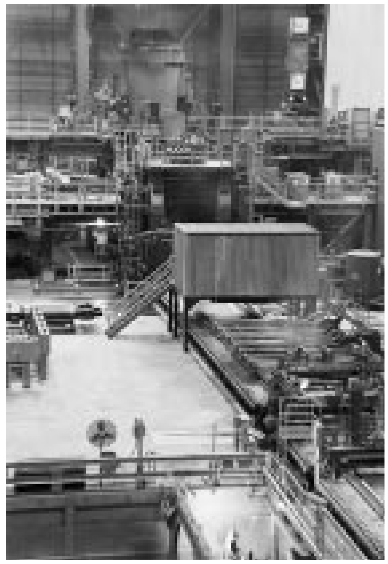

Fig. 3. The CASTRIP process at Nucor Crawfordsville.

TABLE 1. Comparison of Fundamental Casting Parameters Among the CASTRIP Process, Thin Slab Casting, and Conventional Slab Casting

Parameter	CASTRIP® process	Thin slab casting	Conventional slab casting
Strip thickness	1.6	50	220
Casting speed, m/min	80	6	2
Average mold heat flux, MW/m^2	14	2.5	1.0
Total solidification time, sec	0.15	45	1070
Average shell cooling rate, °C/sec	1700	50	12

ical reductions are less than 30%. Two coilers, shown at the end of the line in Fig. 2, allow continuous operation of the casting process. Additional descriptions of the technology, the Crawfordsville plant, and inherent benefits of the Castrip process are described elsewhere [5–7].

A photograph of the CASTRIP process at Crawfordsville is shown in Fig. 3. A ladle of steel, located at the top center of the photo, is mounted on the turret and rotated into casting position. The in-line rolling stand (identified by the “Nucor” sign across its top) can be seen in the middle of the photo. The corrugated steel structure straddling the line downstream of the rolling stand is a surface inspection station. Steel strip can be seen on the line, entering the cooling area. The second pinch roll and shear are located in the bottom right-hand corner of the photo; however, not visible are the two coilers, which are to the bottom right just outside the field of view.

The solidification fundamentals of the twin-roll casting process are quite different as compared to conventional or thin-slab continuous casting. In particular, the interface between the solidifying shell and the mold surface is created and maintained in a completely different manner. Whereas mold powder is utilized in continuous casting, the CASTRIP process does not employ any form of powder or lubricant. Further, the shell and the casting roll travel rotationally in intimate contact down through the melt pool, unlike conventional continuous casting where the mold is oscillated to break contact and facilitate withdrawal of the slab. Table 1 shows values of some key casting parameters for the CASTRIP process compared to conventional thin-and thick-slab casting. As can be seen, the CASTRIP process operates in a regime of heat transfer that is an

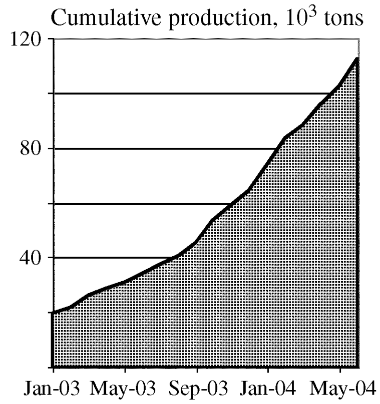

Fig. 4. Cumulative production at the CASTRIP facility, since plant commissioning in May 2002.

Fig. 5. Ladles rotating into and out of casting position during sequence casting at Nucor's CASTRIP facility.

order of magnitude higher than the conventional casting methods. This gives rise to the tremendous difference in average cooling rate during solidification among the three processes and the dramatic difference in time for total solidification. The result of these differences is a high rate of productivity for a small casting unit and a very fine solidification microstructure.

Plant Progress. Hot commissioning of the CASTRIP facility commenced on May 3, 2002 and to date more than 100,000 tons of UCS (Ultra-thin Cast Strip) material has been coiled. Since January 2003, the plant has been operating on a 24-hour cycle, 7 days per week, utilizing four complete crews. Complete staffing for the facility, including management and technical staff, number less than 60. Cumulative production figures from the Nucor facility are shown in Fig. 4, indicating the milestone of 100,000 tons of cumulative production, achieved in May 2004. By the end of June 2004, the plant had produced more than 110,000 tons, cumulatively. Production progress at the facility has accelerated greatly in the second year of operations with key process breakthroughs accomplished in July–August 2003. Nearly 75% of the cumulative production since start-up was completed in the period from May 2003 to May 2004. The increase in production is a direct consequence of the improved yield from the process which has jumped from less than 50% in early 2003 to more than 80% during May 2004. Yield to prime coil is a critical factor in the economic viability of the CASTRIP process, as it is with any capital intensive operation.

One limiting factor on CASTRIP process throughput has been the melting capacity at Nucor's Crawfordsville EAF shop. In addition to feeding the CASTRIP plant, the existing EAF shop also provides more than 2 million tons annually of liquid steel to the thin-slab casting on the same site. Given current market conditions and logistical challenges to optimize sequence casting, the EAF shop will shortly undergo modifications that should allow a greater flow of liquid steel to the CASTRIP facility by the end of 2004.

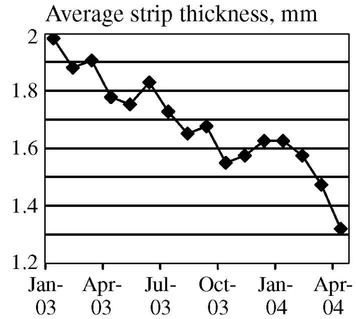

Fig. 6. Average monthly strip thickness produced at the CASTRIP facility.

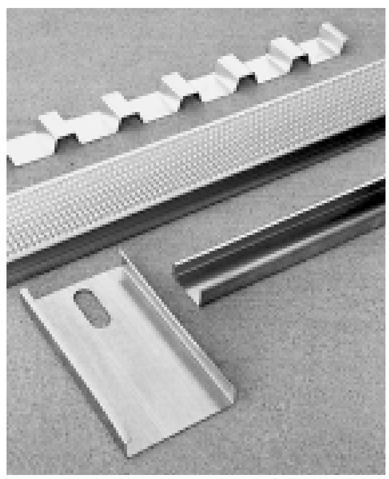

Fig. 7. Typical applications for CASTRIP UCS steel. Photo shows, from the top, structural steel deck, stair tread, purlin, and steel stud.

Sequence casting is standard at the CASTRIP facility with as many as 4 ladles cast in one sequence. Current projections show that sequence length is an important factor in establishing commercial viability of the process. A discussion on the importance of sequence length and other critical factors related to the economic viability of twin roll casting has been provided by Herbertson [8]. The critical hurdle for limiting refractory cost is the production of more than 300 tons (3 ladles) in a sequence and the limiting factor was thought to be the life of the refractory side dams which prevent the flow of liquid steel from either end of the casting pool. The achievement of a 4-ladle sequence, with a total duration of more than 6 hours, indicates the achievement of this important milestone in terms of process economics. Fig. 5 shows a photograph of the CASTRIP plant undergoing a ladle change during sequence casting.

The CASTRIP process is particularly suited for the production of light-gauge steel sheet. When the plant started in mid-2002, the caster produced an average product thickness at just below 2.0 mm. Since that time, the average product thickness has been steadily reduced through a combination of higher casting speeds and greater amounts of in-line hot reduction in the single mill stand. Figure 6 indicates the average monthly thickness from the CASTRIP facility since the beginning of 2003. As indicated, the average thickness has fallen from nearly 2 mm to 1.3 mm over the past 14 months. Further, during April 2004, the plant produced the lightest gauge material to date with a finished thickness of 0.84 mm. This product has since been skin passed and sold to the market as a replacement for cold rolled sheet with excellent results. With the minimum

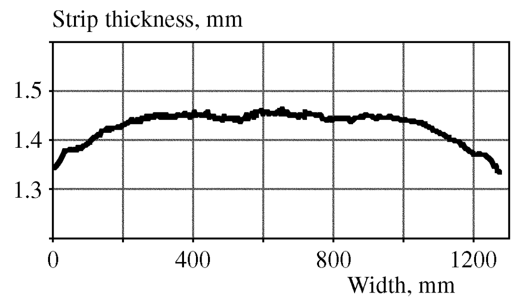

Fig. 8. Typical as-cast UCS strip profile.

gauge produced at the Crawfordsville thin-slab caster and hot mill restricted to 1.5 mm, Nucor is particularly interested in utilizing the CASTRIP process for supply of higher value, lighter gauge, sheet products. The thickness trend shown in the graph indicates the success on this front.

The sale of products from the CASTRIP process has been progressing steadily since mid-2002. Initially, the majority of the UCS (Ultra-thin Cast Strip) had been sent to Nucor's finishing lines at Crawfordsville for pickling, cold rolling, and galvanizing. This provided ample opportunity for inspection, testing, and analysis of the product performance. Further, early sales were limited to Nucor's building products divisions, where they were rollformed into applications such as structural deck. Once again, rollforming operations were closely monitored for product performance. Over time, product applications have broadened to external customers and include a variety of applications, primarily in the construction industry. Small samples from some of the typical end uses are shown in Fig. 7.

Product Attributes. As is the case in any production facility, the continuous monitoring of key process variables is conducted at the CASTRIP plant. Strip thickness is continuously measured throughout the cast using two on-line, x-ray gauges. The scanning x-ray device, which is located before the hot rolling stand, is dedicated to measuring the strip profile, and the second device is used to measure the centerline thickness after the mill. Figure 8 is an example of a typical cast strip profile (averaged over a coil). Strip crown measured at 40 mm from the edge is about 75 μm. Work is currently under way to reduce the overall crown, which is directly related to the profile of the casting rolls. A discussion on casting roll development has been provided elsewhere [3].

Strip surface finish has been characterized using a surface Profilometer (Rank Taylor Hobson Series 120). This instrument uses a diamond tip stylus (tip radius 2 mm) with a resolution of 32 nm. Table 2 compares the surface roughness measurements obtained from as-cast UCS material with strip obtained from conventional hot strip mill. The roughness of the as-cast strip is between 2 to 3 μm in comparison to 1 to 1.5 μm for conventional hot strip mill product. Previous work during the development of the process at the Project M plant in Australia had shown that surfaces smoother than conventional hot strip mill material can be obtained with the use of in-line mill with roll bite lubrication[2] and this development is currently under way at Crawfordsville.

Microstructure evolution in strip casting is fundamentally coupled to the solidification process. The nucleation density during solidification can profoundly influence the austenite grain size and thus, subsequent ferritic microstructures [4]. Under typical cooling conditions on the CASTRIP plant run out table, the microstructure of the as-cast material is a mixture of polygonal ferrite and low temperature transformation products such as acicular ferrite (see Fig. 9). This microstructure can be altered with very low cooling rates to form large polygonal ferrite grains, or through rapid cooling to form bainitic and even martensitic grain structures. Further, research work has shown that dynamic recrystallization of the prior austenite can result in grain refinement and hence a ferrite grain structure in the finished product that is much more akin to conventional hot band [4].

Typical mechanical properties of UCS in-line rolled material produced at the Nucor CASTRIP facility are summarized in Table 2. A majority of the cast material today has been produced to meet ASTM A1011M specifications. As can be seen from Table 3, typical UCS material exceeds the requirement for A1011M Structural Steel Grade 275, according to the

TABLE 2. Comparison of Strip Surface Texture – As-Cast UCS Strip vs. Conventional Hot Rolled Strip

Location	Parameter	As-cast UCS	Conventional hot strip
Top surface	R_a (μm)	2.8	1.33
	RzDin (μm)	18.6	9.7
	S (μm)	101.2	56.6
Bottom surface	R_a (μm)	2.2	1.11
	RzDin (μm)	12.5	9.2
	S (μm)	69.8	60.0

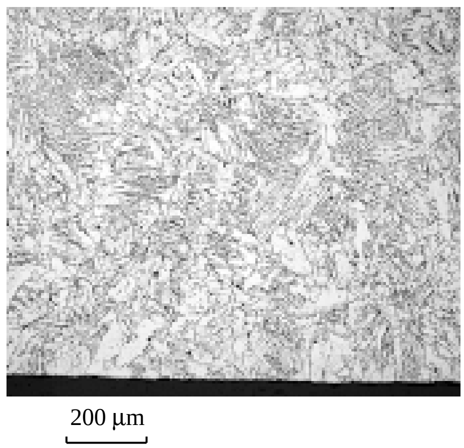

Fig. 9. Typical as-cast UCS microstructure indicating a mixture of polygonal and acicular ferrite.

specification. Grade 275 is a common low-carbon structural grade for applications in construction and manufacturing markets, such as those shown in Fig. 7. Although the microstructure of CASTRIP UCS material is not identical to that of standard hot band, the mechanical properties of the strip have been shown to exceed the specification. Furthermore, UCS material has demonstrated the ability to be pickled, cold rolled, annealed, rollformed, and welded, in addition to other standard finishing operations for structural steel grades.

Achievement of good edges is one of the greatest challenges in strip casting. The region of the side dam in direct contact with the roll is cooled dramatically, making this area more prone to steel freezing and thus skull formation. This can result in poor edge quality and in some cases cause severe operational problems. Effective control of metal flow and solidification in this region is fundamental to the production of good edges. As-cast coils with good edges are routinely produced.

Conclusions. In addition to routine production of strip thicknesses in the range of light gauge steel sheet below 2 mm, a number of other milestones have been attained during the first two years of operation of the CASTRIP process at Crawfordsville:

1. The plant has repeatedly demonstrated the capability of sequence casting 3 or more consecutive ladles (>350 tons) at total casting durations of more than 6 hours. This is a critical factor for process economics.

2. Final strip thickness of as low as 0.84 mm has been produced and successfully processed.

3. Hourly production rates of 60 tons/hr/m have been consistently achieved. This indicates that an annual throughput of more than 500,000 tons is achievable.

TABLE 3. Properties of Typical UCS Material Produced by the CASTRIP Process. The Material Conforms to ASTM A1011M SS Grade 275

Material	Yield strength, MPa	Tensile strength, MPa	Elongation, %
ASTM A1011 – Grade 275 minimum	275	380	15
UCS (rolled) – typical	315	420	26

4. Castability of low carbon steel grades with higher copper levels (up to 0.5%) has been demonstrated. Possible benefits from lower incoming scrap quality without degenerated product properties are foreseen.

5. Despite a clear focus on low-carbon structural grades, successful casting trials with stainless (409), medium carbon (0.25), higher phosphorous (0.1%) and electrical steels have been conducted.

The production of flat rolled products utilizing the CASTRIP process has many advantages over conventional casting and rolling technology, including lower capital and operating costs, reduced energy usage and emissions, thinner higher value products, and a smaller, more flexible operating regime. Further, due to its lighter gauges (<1.5 mm) and excellent surface quality, CASTRIP products can be substituted for cold rolled sheet in many applications and will likely create a new product category for flat rolled sheet products known as UCS. Still to be confirmed for the technology are the overall conversion costs and life of other critical components. This information will be obtained as the plant works its way towards full operating rates, over the next year or so.

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