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THE CASTRIP® PROCESS – RECENT DEVELOPMENTS AT NUCOR STEEL'S COMMERCIAL STRIP CASTING PLANT

D. J. Sosinsky,[1] P. Campbell,[1]
R. Mahapatra,[2] W. Blejde,[2]
and F. Fisher[2]

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The CASTRIP® facility at Nucor Steel's plant in Crawfordsville , Indiana, has been in operation since May 2002. Nucor has also commenced construction of its second strip casting plant in Blytheville, Arkansas. The Crawfordsville plant produces low carbon Ultra-Thin Cast Strip (UCS) material in the thickness range of 0.8 to 1.5 mm with a broad range of mechanical properties which are used in applications replacing cold rolled and hot rolled steel sheet. This paper will report on the recent progress made at the Crawfordsville plant, specifically, the effect of dissolved gasses, such as hydrogen and nitrogen, on castability of UCS produced at the CASTRIP® facility.

Introduction. The direct casting of thin low-carbon steel strip at commercial production rates has been proven at Nucor Steel's CASTRIP® facility at Crawfordsville, Indiana. Nucor's CASTRIP® machine was installed in 2002 and since that time the plant has produced Ultra-Thin Cast Strip products (UCS). Product quality and mechanical properties of UCS material are suitable for a broad range of applications as a direct substitute of cold rolled and hot rolled steel sheets. Products shipped have been mostly in the thickness range of 0.8 to 1.5 mm. This paper provides an update on the status of CASTRIP® technology and recent progress made at the Crawfordsville facility.

CASTRIP® Process Overview. The CASTRIP® process is based on the same concepts that Henry Bessemer patented in mid-19th century. The process essentially consists of two counter-rotating rolls as schematically shown in Fig. 1. The molten steel delivered from the top solidifies on the surfaces of the two casting rolls. This results in the formation of two separate shells which are joined together at the roll nip to form a continuous solid strip.

Although the casting concept is simple, the underlying process fundamentals are extremely challenging. Thus development of this technology for application at a commercial production level has taken a considerable amount of time. More details on the various aspects of process development can be obtained from previously published papers [1–7].

The CASTRIP® process has many inherent advantages over conventional casting and rolling technologies. These include a smaller foot print, lower capital cost, simpler and more flexible operating plants, more tolerance to high residual scrap feed, and superior environmental performance. Strip casting eliminates a number of intermediate processing steps that exist in conventional strip production routes, as illustrated in Fig. 2. As a consequence, the energy consumption and corresponding

[1] Nucor Steel, 4537 South Nucor Rd, Crawfordsville, IN 47933, USA.
[2] Castrip LLC, 1915 Rexford Rd, Suite 150, Charlotte, NC 28211, USA.

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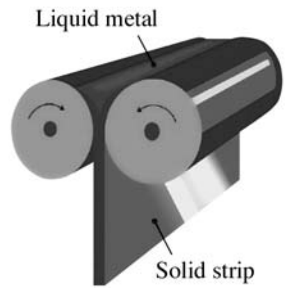


Fig. 1. Schematic illustration of twin-roll strip casting process.

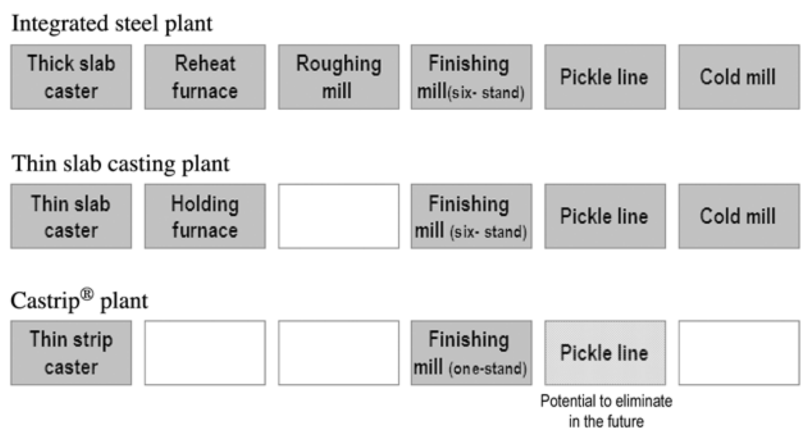


Fig. 2. Processing steps involved in strip production via conventional hot/cold rolling and CASTRIP® process routes.

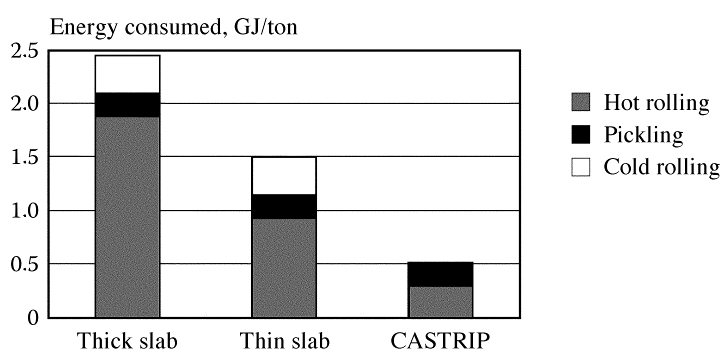


Fig. 3. Comparison of energy requirements for strip production via conventional hot/cold rolling and CASTRIP® process routes.

greenhouse gas emissions associated with the CASTRIP® process are considerably lower. Results obtained from recent modelling calculations, presented in Fig. 3, have confirmed a substantial savings in energy with the CASTRIP® process.

CASTRIP® Process Metallurgy Overview. The metallurgical regime associated with the CASTRIP® process is dramatically different from conventional casting. This is a consequence of extremely high heat flux and solidification rates encountered in strip casting process (see Table 1). Management of high heat flux is indeed challenging; however, rapid cool-

TABLE 1. Comparison of Key Process Parameters Associated with Various Casting Technologies

	CASTRIP® process	Thin slab casting	Thick slab casting
Strip thickness, mm	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

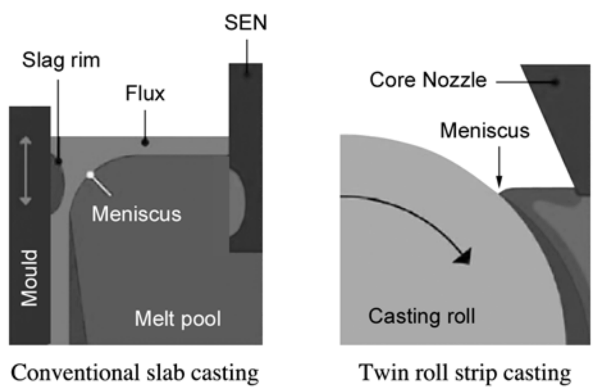


Fig. 4. Schematic comparing the mould areas in the CASTRIP® process versus a conventional slab caster mould.

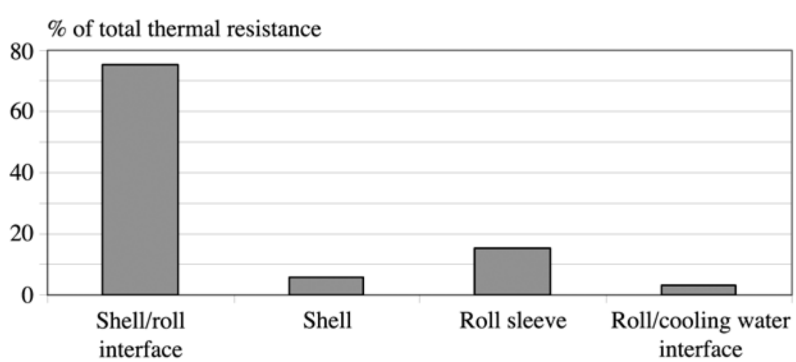
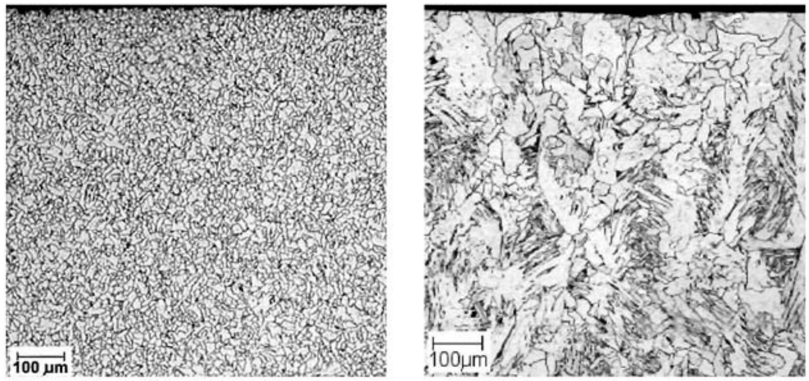


Fig. 5. Significance of various thermal resistances to heat transfer in CASTRIP® process.

ing rates can produce unique microstructures and other product features which cannot be readily obtained with conventional casting processes.

Key process differences between the casting processes mainly arise from the fact that the CASTRIP® process does not utilize any mould powder and, secondly, the mould and shell travel at the same speed (i.e., no mould oscillation), as illustrated in Fig. 4. Therefore the nature of shell/mould interface which governs heat transfer rates is fundamentally different in the CASTRIP® process as compared to conventional continuous casting processes. As there is no mould powder used in the



a *b*

Fig. 6. Comparison of strip microstructures obtained with (*a*) conventional casting/rolling technologies and (*b*) the CASTRIP® process.

a *b* *c*

Fig. 7. Cups drawn out of (*a*) CASTRIP® UCS sheet, (*b*) conventional hot rolled sheet, and (*c*) cold rolled and annealed sheet.

CASTRIP® process, significantly better contact is established between roll surface and solidifying shell, resulting in extremely higher heat transfer and cooling rates.

In the CASTRIP® process, the shell/roll interface offers the maximum resistance to heat flow, as shown in Fig. 5. Thus factors which can influence the wetting characteristics between melt/roll surface, including the levels of dissolved gases and gas atmosphere above the melt pool, have a profound impact on the rate of heat removal. The total solidification time in the CASTRIP® process is between 100 and 200 milliseconds; however, surface quality of the UCS is determined during the first 20 to 30 milliseconds. Therefore, control of heat removal across the roll surface is critical to eliminating casting defects due to stress buildup. Thus considerable attention has been devoted towards determining the fundamentals of heat removal and solidification mechanisms across the roll surface.

CASTRIP® UCS product microstructures are vastly different from conventional hot rolled strip, as shown in Fig. 6. Contrary to conventional hot strip mill products which undergo large hot reductions that break up the structure and enhance recrystallization kinetics, microstructure evolution in the CASTRIP® sheet is fundamentally coupled to the solidification process. Coarser austenitic grains which are typical of strip casting can be transformed to a range of microstructures, thereby making it possible for strip casting to produce unique combinations of strength and formability.

Another important feature of CASTRIP® UCS products is the isotropic nature of mechanical properties. This attribute can be better appreciated from Fig. 7, which compares photographs of cups drawn from UCS and conventional hot

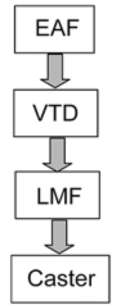


Fig. 8. Steel processing route at Crawfordsville CASTRIP® plant.

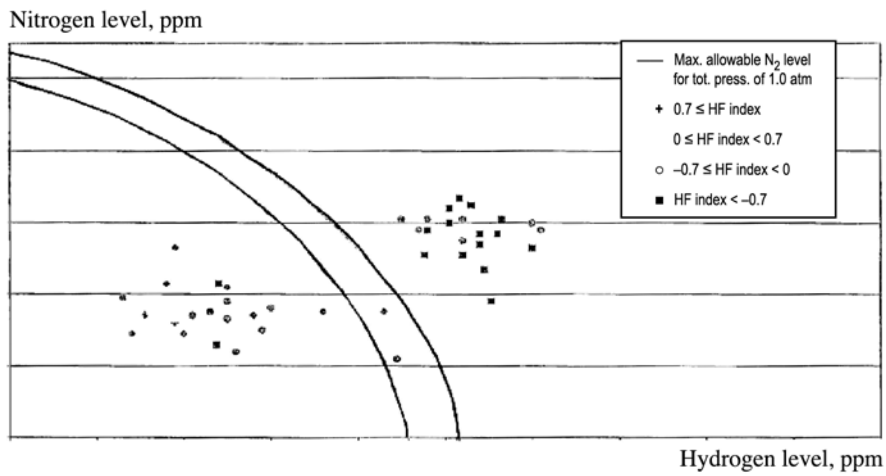


Fig. 9. Influence of hydrogen and nitrogen gas levels on castability.

and cold rolled strip. The unevenness associated with the rim is a good measure of isotropy and, as can be seen, CASTRIP® UCS products exhibit a superior performance. More details on fundamental aspects of CASTRIP® metallurgy can be obtained from earlier publications [8–11].

Crawfordsville Plant Operation

Steel Treatment Facility. The Electric Arc Furnace (EAF) shop located in Nucor's Compact Strip Production (CSP) melt shop provides steel to the CASTRIP® plant. Ladles (105 tons) are transported from the melt shop to the CASTRIP® plant via rubber-tired carriers. The steel treatment facility at the CASTRIP® plant consists of a Vacuum Tank Degasser (VTD) and a Ladle Metallurgy Furnace (LMF). The steel processing route is shown schematically in Fig. 8. Control of dissolved gases such as hydrogen and nitrogen is critical as higher levels can dramatically reduce mould heat transfer rates and thus be detrimental to castability. Following treatment at the VTD, the ladle is processed at the LMF to trim melt composition and temperature to the desired specification. The plant typically produces low carbon Mn/Si killed steel. At the end of the LMF treatment, the ladle is sent to the caster.

The effect of dissolved gases is demonstrated in Fig. 9, which shows an improvement in castability with heats having lower levels of hydrogen and nitrogen. This can be contrasted with heats containing higher levels of H_2 and N_2. As Fig. 8 illustrates, steel destined for CASTRIP® is degassed. This is to ensure that both hydrogen and nitrogen levels remain low enough to ensure good castability. The solubility limit of these gases is significantly reduced with the onset of solidification. Solidification causes the non-soluble gases to be ejected. As the levels of H_2 and N_2 increase, the pressure buildup at the interface between the steel and the roll increases, subsequently resulting in reduced heat transfer rates.

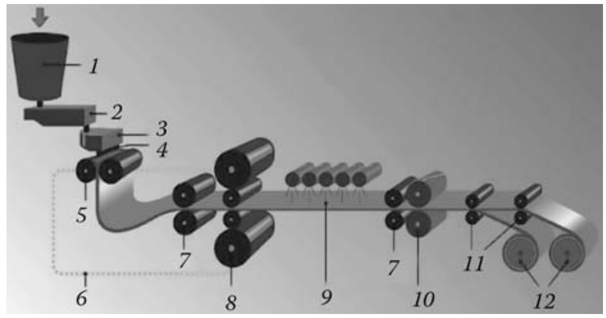


Fig. 10. Schematic of Crawfordsville CASTRIP® casting machine: *1*) ladle; *2*) tundish; *3*) transition piece; 4) core nozzle; *5*) casting rolls; *6*) hot box; *7*) pinch rolls; *8*) hot rolling stand; *9*) water cooling; *10*) shear; *11*) deflector rolls; *12*) coilers.

TABLE 2. Crawfordsville Casting Machine Specifications

Unit	Crawfordsville specification (in metric units)
Casting line length (centre turret to No. 2 coiler)	58.68 m
Pass line elevation	EL + 800 mm
Ladle heat size	110 tons (metric)
Tundish weight	18 tons
Caster type	500 mm diameter twin roll
Max caster width	1345 mm
Steel grade	Low carbon Mn/Si killed
Product thickness range	0.76 to 1.8 mm
Casting speed	80 m/min typical, 120 m/min max
Max coil size	25 tons
Inline rolling mill	Single stand, 4 high with hydraulic roll bending and automatic flatness control
Work roll dimensions	475 × 2050 mm
Backup roll dimensions	1550 × 2050 mm
Maximum rolling force	30 MN
Cooling table	10 top and bottom headers
Coiler size	2 × 40 tons with belt wrappers
Coiler mandrel	762 mm
Annual capacity (84% metal in mold time and 91% yield)	540 kt/yr

Casting Facility. A cross-section through the casting machine showing the key components is presented in Fig. 10. Specifications for the Crawfordsville CASTRIP® plant are summarized in Table 2. Molten steel from the ladle is transferred to a tundish which then feeds a smaller tundish (referred to as the transition piece). Steel from the transition piece flows into

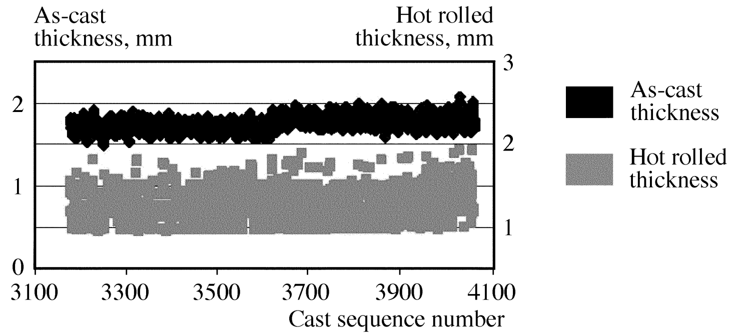


Fig. 11. Cast and rolled strip thickness for 8000 coils produced at the CASTRIP® plant.

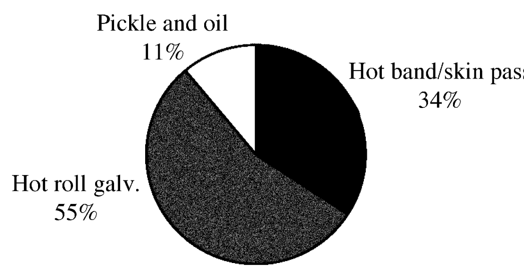


Fig. 12. Breakdown of CASTRIP® shipments by processing route.

the mould via metal delivery nozzles located between the casting rolls (referred to as core nozzles). After exiting the casting rolls, the solidified strip enters a chamber with a controlled atmosphere, to inhibit scale formation. This chamber is referred to as the "hot box." The strip is then directed to a pinch roll which provides steering control and, in combination with a downstream pinch roll, maintains tension on the strip during rolling. The in-line single stand hot rolling mill is capable of approximately 50% reduction. The strip leaving the mill is cooled by the run out table sprays, cut by a shear, and then coiled by one of the two coilers.

CASTRIP® – Plant Production. The Crawfordsville plant commenced operation in May 2002. Typical casting sequences are 5 to 6 heats; however, a casting sequence record was established in late 2007 where 24 ladles were cast during one sequence over a span of 38 hours.

The thickness of the as-cast strip exiting the roll nip is primarily governed by the heat transfer rates in the mould, steel temperature, and the solidification time, which in turn is determined by steel height in the mould and casting speed. Plant data from over 8000 coils produced in 2007 and early 2008 indicate that casting speed varied between 55 to 80 m/min, resulting in as-cast strip thickness in the range of 1.6 to 1.9 mm (see Fig. 11). The cast strip is typically subjected to 15 to 40% hot reduction determined by customer's thickness requirements. As shown in Fig. 11, the final thickness of material produced during this time period was predominantly in the range of 1.0 to 1.5 mm.

Product Mechanical Properties and Applications. Products produced at the CASTRIP® facility in Crawfordsville plant follow one of three downstream processing routes prior to shipment to the market: (1) black hot-rolled UCS is levelled and trimmed, (2) pickled UCS is processed and trimmed on one of Crawfordsville's two pickle lines, and (3) galvanized material is pickled, trimmed, then sent through the site's galvanizing line. A breakdown of shipments by product group is shown in Fig. 12. CASTRIP® UCS competes against hot rolled coil in gauge ranges between 1.3 and 1.5 mm. Below 1.3 mm, UCS is used as a substitute for cold rolled sheet, either as pickled and oiled or as a substrate for galvanizing. Applications are mainly related to the construction industry, but increasingly UCS products have been utilized in more demanding uses.

TABLE 3. Typical Properties of UCS Material Compared to ASTM A1011 Specification for Sheet Steel

ASTM A 1011M	Minimum ASTM requirements			Typical CASTRIP® UCS properties		
	Yield strength, MPa	Tensile strength, MPa	Elongation, %	Yield strength, MPa	Tensile strength, MPa	Elongation, %
SS Grade 275	275	380	15	325	430	28
SS Grade 340	340	450	11	375	475	21
SS Grade 380	380	480	9	440	530	18

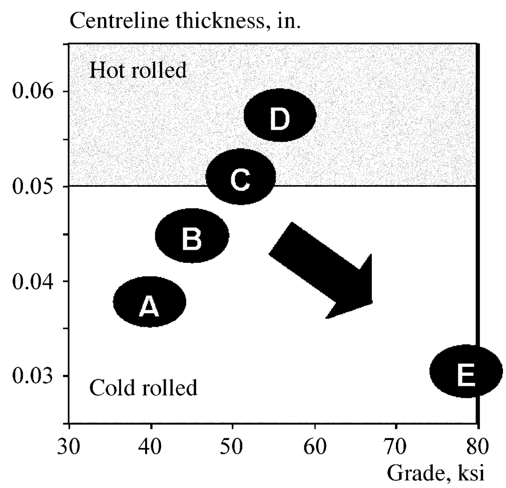


Fig. 13. Typical gauge and strength of UCS coils produced at Nucor Crawfordsville with end application areas: A – steel framing and structural steel deck; B – racking and framing; C – steel framing; D – structural purlins and racking; E – steel framing.

A wide range of mechanical properties is achieved through control of hot reduction, coiling temperature, and steel composition. Typical mechanical properties of UCS material are summarized in Table 3. As can be seen, UCS material properties exceed the requirements of ASTM A1011 specifications for sheet steels. In addition to the A 1011 specification, a new specification was developed for steel sheet produced via the twin-roll casting process. Approved in 2005 as ASTM A1039, CASTRIP® UCS products are also sold under this standard.

To date, CASTRIP® UCS material has been shipped to the market for a variety of applications (Fig. 12). End-use applications of UCS products have expanded greatly since the product was introduced in 2002. A summary of current UCS products expressed in terms of thickness and strength, including example applications, is summarized in Fig. 13.

Summary. Since start-up in 2002, Nucor's CASTRIP® plant in Crawfordsville, Indiana, has shipped UCS steel sheet to end use markets. The process is ideally suited for the production of light-gauge, hot rolled sheet, competing with both conventional hot rolled products as well as cold roll applications. The Crawfordsville plant continues to increase annual production and widen the range of products offered to end users. The success at the Crawfordsville plant has provided Nucor with the confidence to build a second CASTRIP® facility – construction is underway in Blytheville, Arkansas. Similar to the CASTRIP® plant at Crawfordsville, the Blytheville plant will utilize liquid steel from an existing Nucor steelmaking operation (Nucor-Yamato Steel) to cost-effectively expand the company's product offering.

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