The Status of Twin-Roll Strip Casting Technology – Castrip® Process

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THE STATUS OF TWIN-ROLL STRIP CASTING TECHNOLOGY – CASTRIP® PROCESS

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Abstract

The CASTRIP® Process is aimed at producing steel sheet between 0.7 and 2 mm in thickness, at an annual capacity of 500,000 tonnes, utilizing twin-roll strip casting technology. Commissioning of the world’s first commercial strip caster for low-carbon steel production, utilizing CASTRIP technology, began in May 2002 at Nucor Steel, Crawfordsville, Indiana. Since that time, the plant has been ramping up production, improving product yield and quality, and selling steel sheet to the construction market. With many inherent advantages including low capital investment, reduced environmental impact, ability to cast thin, high-value products, compact plant size and potential for new sheet products, CASTRIP technology is poised to create a new business model for the steel industry. This paper will report on progress made at the Nucor plant towards commercialization of this new technology.
Introduction

The production of steel strip directly from liquid steel has been the dream of steel industry technologists for over 150 years. 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, U.S.A. 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.

The CASTRIP process was jointly developed by BlueScope Steel and IHI beginning in 1989, under the code name Project ‘M’. Details of all the collaborative efforts expended towards development of CASTRIP® technology over the last decade have been presented elsewhere [1-4]. In late 1999, Nucor Steel joined the effort and committed to build a full commercial plant at its existing steel facility in Crawfordsville IN [5-7]. At that time, Castrip LLC was created to make the technology and patents related to CASTRIP process available to third parties; Castrip LLC is owned jointly by BlueScope Steel (47.5%), IHI (5%) and Nucor (47.5%).

CASTRIP process fundamentals

Plant layout

Figure 1 is a schematic representation of the general layout of the Nucor plant. Molten steel is transported to the CASTRIP facility from the existing Crawfordsville EAF, via rubber-tired carrier in 110-tonne ladles. Ladles are pre-treated in a LMF (ladle metallurgy furnace), located within the strip casting plant. The main components of the CASTRIP process are indicated in Figure 1, starting with the ladle turret and continuing to the coilers. A single rolling stand is capable of 50% reduction, however typical reductions are less than 30%. Included in the CASTRIP facility are work areas for refractories and roll preparation.

![Figure 1. Schematic of Nucor CASTRIP plant layout.](image-url)
A photo of the interior of the plant during operations is shown in Figure 2. A ladle of steel is visible at the top of the photo with the casting area immediately in front of and below the turret. The rolling stand is next (indicated by the “NUCOR” sign) with the run out table and cooling area thereafter. The structure straddling the run out table is a surface inspection station. The bottom right corner of the photo shows the shear and second pinch roll with the coilers just out of view.

Figure 2. Photo of the interior of Nucor’s CASTRIP facility

Process Description

A schematic elevation of the strip-casting machine is shown in Figure 3. As can be seen, strip casting enables the elimination of intermediate process steps which exist in conventional strip production resulting in a process that is not only simpler, but in many respects more challenging from the process point of view. Molten steel is delivered from the ladle into the mould via a tundish followed by a metal distributor (or transition piece) and a set of delivery nozzles placed between the two casting rolls. After solidification on the casting rolls (0.5 m diameter), the strip exits through an inert gas chamber that is used to prevent the formation of scale. The strip leaving the mill is cooled, cut to length by a shear and then coiled on one of two coilers. The total line length is approximately 60 meters. The plant is fully automated requiring minimal operator intervention. Extensive use has been made of robotics.
Plant experiences

Plant Production

Hot commissioning of the CASTRIP facility commenced on May 3, 2002 and to date more than 80,000 tonnes of UCS (Ultra-thin Cast Strip) material has been coiled. Since Jan 2003, the plant has been operating on a 24 hour cycle, 7 days per week. Quarterly production figures from the Nucor facility are shown in Figure 4. As indicated, progress at the plant was slow until mid 2003. During July 2003 a fundamental change was made in the process that provided improvements in yield, quality and throughput. Further increases in production by the plant are expected as Nucor increases capacity of the Crawfordsville EAF shop, heretofore a limiting factor on steel available to cast.
Current development focus

During ramp-up of the CASTRIP facility at Crawfordsville, the main focus has been to cast low carbon steel sheet (0.04 to 0.06% carbon), at a width of 1345 mm. Owing to the unique relationship among casting speed, solidification rate and casting thickness, the twin-roll casting process is ideally suited for production of thin strip. Machine throughput in strip casting increases with decreasing cast strip thickness, unlike conventional strip production processes where productivity declines. Thus, the aim thickness for casting has tended downwards during the commissioning phase and now stands at 1.6 mm or less. This equates to a casting speed of 80 m/min with an annualized rate of more than 500,000 tonnes. Current operations reduce the thickness of the cast material further by rolling in the in-line mill between 10 to 15%. Thus, the bulk of the UCS products have been in the thickness range of 1.3 mm to 1.6 mm.

Downstream processing of the material, prior to sale to the market, has included some of the following steps: skin passing, edge trimming, pickling, cold rolling and galvanizing.

Key Process Milestones attained

In addition to routine production of strip thicknesses in the range of 1.3 to 1.6 mm, a number of other milestones have been attained during the commissioning and ramp-up of the process; these include:

1. The plant has repeatedly demonstrated the capability of sequence casting 3 or more consecutive ladles (>330 tonnes). This is a critical factor for process economics
2. Final strip thickness of as low as 1.1 mm has been produced and successfully processed.
3. Hourly production rates of 60 tonnes/hr/m have been consistently achieved. This indicates an annual throughput of >500,000 tonnes
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.

Product quality

Satisfactory attainment of strip quality attributes can only be produced through careful control of metal delivery, mould heat extraction & solidification, mould thermo-mechanical behavior, edge technology, microstructure evolution and in-line hot rolling. Process fundamentals associated with these aspects have been reported elsewhere [3]. Descriptions of some of the product attributes achieved to date at the Crawfordsville plant are presented in this section.

Surface quality

Strip surface texture
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 1 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 underway at Crawfordsville.

Table 1: Comparison of strip surface texture – as-cast UCS strip vs. conventional hot rolled strip

<table>
<thead>
<tr>
<th>Location</th>
<th>Parameter</th>
<th>As-cast UCS</th>
<th>Conventional hot strip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top surface</td>
<td>( R_a ) (µm)</td>
<td>2.8</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>( R_zD_{in} ) (µm)</td>
<td>18.6</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td>( S ) (µm)</td>
<td>101.2</td>
<td>56.6</td>
</tr>
<tr>
<td>Bottom surface</td>
<td>( R_a ) (µm)</td>
<td>2.2</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>( R_zD_{in} ) (µm)</td>
<td>12.5</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>( S ) (µm)</td>
<td>69.8</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Scale

One of the inherent advantages of strip casting is the opportunity to control and possibly prevent the formation of surface scale. This is due to the ability to contain the strip in a protective atmosphere immediately following casting and into the rolling mill. Although the work on atmosphere control is preliminary at this stage, scale formed during the process has been measured via metallographic examination. Figure 5 compares the scale levels of as-cast UCS with that of a conventional hot strip material. As can be seen, the thickness of the scale formed on the surface of the as-cast UCS is similar to that of the hot strip material, i.e. 4 to 8 µm.

Figure 5. Micrographs showing scale levels on: (a) as-cast UCS (b) conventional hot rolled strip (note that darker region on the top in both micrographs is the sample mount)

Scale levels on the strip have a significant impact on process economics. Strip casting offers significant potential to further reduce scale levels by effective shrouding and strip temperature control. Future developments will concentrate on producing scale-free surface and thereby eliminating pickling, which could lead to a significant reduction in operating costs.

Internal Quality
Solidification microstructure
Figure 6 shows the as-cast microstructure of UCS material. As can be seen, the structure is characterized by a fine dendritic solidification structure, which is consistent with previous observations [8]. The straight centerline, apparent in the meeting of the dendrites from either strip surface, is a reflection of uniform solidification on both casting rolls.

![Figure 6. As-cast UCS solidification microstructure.](image)

Segregation
Segregation levels through the thickness of the strip have been characterized with “Quantitative elemental x-rap mapping”. A typical x-ray map for Phosphorous, presented in Figure 7, shows uniform levels thorough the strip without any notable segregation. This is a consequence of the solidification rates prevalent rates in strip casting, which do not allow macro segregation of residual elements to occur. In fact, solidification during the CASTRIP process is complete in 0.15 seconds at an average shell cooling rate of approximately 1700 °C/s.

![Figure 7: Quantitative full thickness X-ray map of Phosphorous from as-cast UCS material](image)

Internal soundness
Radiography was used to assess the internal soundness of the strip, i.e. analyze for porosity. Figure 8 is a radiograph of in-line hot rolled UCS subjected to less than 15% reduction. As can be seen, there are no voids/porosity present in the material (note that internal voids would appear as white spots on the radiograph). A major contributing factor to porosity is the degree
of non-uniformity in the solidification front during strip casting. Poor control over initial solidification combined with the rapid shell growth inherent in strip casting can lead to problems both on the strip surface and in the interior.

Figure 8 – Radiography of UCS material (in-line hot rolled)

**Inclusion composition and size distribution**

An assessment of inclusions present in strip produced via the CASTRIP process was carried out using a Cameca SX50 Micro Probe Analyzer. The deoxidation practice utilized at the CASTRIP plant relies on silicon and manganese as the killing agents. Micro probe analysis showed the presence of fine aluminum-manganese-silicate type of inclusions. Figure 8 compares the size distribution of inclusions found in as-cast UCS and conventional hot rolled strip. The figure indicates that inclusions are typically 2 to 5 µm in size for UCS, which is similar to that of hot strip samples, despite the fact that no hot reduction has occurred. Finer inclusions in strip cast material are a direct outcome of rapid solidification, which reduces the time available for inclusion agglomeration and growth.
Figure 9. Comparison of inclusion size distribution measured in (a) as-cast UCS and (b) conventional hot rolled strip.

**Edge Quality**

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 and an example of a coil edge is shown in Figure 10.

![Figure 10. Photograph of an untrimmed, as-cast UCS coil edge.](image)

**Strip Profile**

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 11 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 um. Work is currently underway to reduce the strip crown.
Strip microstructures and mechanical properties

UCS microstructures
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 normal cooling conditions, the microstructure of the as-cast material is a mixture of polygonal ferrite and low temperature transformation products such as acicular ferrite (see Figure 12).

Figure 13. Typical as-cast UCS microstructure.

UCS mechanical properties
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 specification. As can be seen from Table 2, UCS material
exceeds the requirement for Grade 275, according to the specification. Grade 275 is a common low carbon structural grade in the U.S markets for application in construction and manufacturing markets.

Table 2. Properties of typical UCS material produced by the CASTRIP process. The material conforms to ASTM A1011M SS Grade 275.

<table>
<thead>
<tr>
<th></th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A1011 – Grade 275 minimum</td>
<td>275</td>
<td>380</td>
<td>15</td>
</tr>
<tr>
<td>UCS (rolled) – typical</td>
<td>315</td>
<td>420</td>
<td>24</td>
</tr>
</tbody>
</table>

Conclusions and Next Steps

The start-up of the CASTRIP process at Nucor’s Crawfordsville plant marks the first commercial strip casting installation for the production of plain-carbon steels. Commissioning has been proceeding well, although not without the normal challenges of a new technology. To date, the CASTRIP process has demonstrated the following key strip casting milestones:

- Product quality of UCS from the CASTRIP process has been shown to be suitable as a direct substitute for hot rolled coil as well as feed for cold rolling operations.
- Strip thicknesses as low as 1.1 mm have been produced. The majority of UCS produced has been between 1.3 and 1.6 mm.
- UCS product has been galvanized without cold rolling, with properties suitable for construction applications.
- Sequence lengths of 3 ladles and greater (> 330 tonnes) have been regularly achieved. This is a critical factor for process economics.
- Operating costs per tonne are constantly being reduced as throughput continues to climb. Critical cost elements (refractories, casting rolls) are performing at expected levels.
- In addition to low-carbon grades, trial casts have been performed on stainless and other carbon grades, with promising results.

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.

REFERENCES


