Recent developments with ultrathin cast strip products produced by the Castrip<sup>®</sup> process

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Abstract
Recent product developments at the Castrip facility at Nucor’s Crawfordsville, Ind., plant have focused on expanding its range of light-gauge hot rolled products. This paper presents an overview of these recent product development experiences.

Keywords
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Recent Developments With Ultrathin Cast Strip Products Produced by the Castrip® Process

Since the start of commercial production at Nucor Steel's Indiana Castrip® facility (located in Crawfordsville, Ind.), efforts have been under way to expand the product range. Attention initially focused on the development of grades based on plain low-carbon-manganese steel, eventually progressing to microalloyed steel, particularly with the use of niobium.  

This paper provides an update of the continuing progress in microalloying (use of niobium and/or vanadium), along with work related to other alloying options such as higher carbon contents (0.2–0.3 wt. %), higher manganese content (up to 1.30 wt. %), and higher copper contents (0.2–0.4 wt. %). Each of these approaches is of interest because they all influence the hardenability of UCS steels. Hardenability is an important attribute of UCS products, given the relatively large austenite grain size of UCS material and the resulting significant effects on the final microstructure and mechanical properties. These effects can be dramatic, as has been reported previously in the case of niobium additions. Understanding the role of copper in UCS products is also of particular interest, as it is intended that the Castrip process will be able to employ grades of scrap typically higher in residual copper content. This is of interest with the ever-changing availability of various grades of scrap. Also, the ability to rely on locally generated (typically post-consumer) scrap will grow as a consideration in the production of thin steel.  

In addition to alloying effects, a processing approach is outlined that involves limited cold reduction coupled with recovery annealing, to produce a high-strength, light-gauge product with sufficient ductility to meet the requirements for cold formed sections used in residential framing. For this processing route, both plain low-carbon and niobium-microalloyed steels have been studied to explore the strength-ductility potential with UCS substrate.  

Ultrathin Cast Strip Production via the Castrip Process

Hot Rolled Strip — The details of the Castrip process have been reviewed elsewhere. The following is a review of the relevant aspects of the process, as they relate to the final mechanical properties achieved in UCS products. The Castrip process, as with all twin-roll casting operations, utilizes two counter-rotating rolls to form two individual sheets that are formed into a continuous sheet at the roll nip. The main components of Nucor Steel's Castrip facility in Indiana are indicated in Figure 1. The casting speed is typically in the range

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Main components of the Castrip process.

Figure 2

 Typical worst-case field showing globular inclusions found in UCS steels.

of 60–100 m/minute, and the average strip thickness is typically 1.8 mm or less. The steel type used for the grades in current production is a low-carbon (≤0.05 wt. %) manganese-silicon steel. This alloy design is employed to ensure generation of liquid deoxidation products of MnO and SiO₂ during the casting process to avoid clogging and to enhance the heat transfer rate to the casting roll. The rapid solidification rates possible with the strip casting process can, with control of certain parameters, promote a more uniform distribution of globular inclusions (Figure 2).

A benefit of the Castrip process is that it avoids the formation of type II MnS stringer inclusions, which are often present in Al-killed steels produced from conventional slab casting. The globular inclusions present are also not significantly elongated by the in-line hot rolling process, due to the limited extent of hot reduction, thereby enhancing the performance of UCS products during subsequent forming, shearing or punching operations. In the Castrip process, the resultant inclusion/particle populations are tailored to achieve particle-stabilized intragranular nucleation of acicular ferrite. The size range of the globular inclusions in UCS products typically varies from about 10 µm down to very fine particles, less than 0.1 µm. A large proportion of the inclusions are in the 0.5–5 µm size range. The larger 0.5–10 µm size non-metallic inclusions play an important role in the development of the final microstructure, since they are the particles that are effective in nucleating acicular ferrite. Some of these inclusions are composed of a complex mixture of phases including MnS, TiO and CuS.

Another microstructural feature of the Castrip process is the generation of a relatively large austenite grain size, which is significantly larger than the austenite grain size produced in hot rolling at the exit of a conventional finishing mill. This coarse austenite grain size, in conjunction with the population of tailored inclusion/particles, assists in the particle-stabilized intragranular nucleation of acicular ferrite. A representative microscopic illustration of the formation of acicular ferrite microstructures is shown in Figure 5.

The in-line hot rolling mill is generally utilized for reductions of 10–50%. On the runout table (ROT), there is a water cooling section utilizing air mist cooling. Control of the cooling rates through austenite transformation assists in achieving the desired microstructure and resultant properties of the UCS products.

Hot reductions greater than 20% will induce recrystallization of austenite in plain low-carbon steels (i.e. without niobium additions). This in turn reduces the austenite grain size and its hardenability so that the volume fraction of acicular ferrite is reduced on transformation and a reduction in strength is observed. Countermeasures such as alloying with elements associated with increased hardenability, an increase in the cooling rate during spray cooling on the ROT, and/or niobium microalloying additions to prevent austenite recrystallization are available options for the production of thinner and stronger UCS steels with the desired microstructure and mechanical properties.

Hot Dip Galvanized Strip — Galvanized UCS products are produced at Nucor Steel-Indiana utilizing a conventional continuous hot-dip galvanizing line (CGL). Coils are lap welded at the entry end to ensure continuous operation. The steel strip then proceeds through a cleaning section utilizing an alkali cleaner. The initial preheating section of the furnace is 20 m long. This section is heated by open burners and does not have a specific atmosphere. There is a closed radiant tube section which is 10 m long and utilizes a hydrogen-nitrogen atmosphere. The strip then is jet cooled to the pot immersion temperature (400–480°C), run through the cooling tower, in-line skinpass and tension leveling, and finally coiled at the exit end of the line.

The current galvanized UCS products are processed using conventional line speeds (60–100 m/minute) and processing conditions appropriate for the strip thickness and coating weight (490 to 690 as described in ASTM A653). For the galvanized products discussed in this paper, coil strip temperatures of 625–750°C were employed in the radiant tube section of the furnace.

Higher-Strength Microalloyed Steels

Niobium-Microalloyed UCS Steels — The current production of plain low-carbon steel products has provided a range of UCS products covering structural grades with yield strengths from 275 to 580 MPa. Higher-strength UCS products have recently been developed with yield strength levels up to 550 MPa using microalloying additions of niobium. The current range of plain low-carbon steel (base composition from Table 1) can be applied to achieve yield strength levels up to 380 MPa. However, the available thickness range for grades with minimum yield strengths of 340–380 MPa is limited by this approach because of the reduction in hardenability from the austenite grain refinement from hot rolling.

Niobium-microalloyed UCS steels can significantly extend the strength and thickness range potential for UCS products through suppressed austenite recrystallization and enhanced hardenability mechanisms. By maintaining a larger austenite grain size in conjunction with the inclusion engineering practices discussed above, particle-stabilized intragranular nucleation of acicular ferrite in the niobium-microalloyed UCS steels can continue to represent a substantial portion of the microstructure. The enhanced hardenability provided by niobium suppressed the formation of proeutectoid ferrite and promoted the formation of bainite. A range of niobium-microalloyed steels have been successfully cast by the Castrip process with the niobium contents systematically varied from 0.014 to 0.084 wt. %. The compositions of the niobium-microalloyed trial heats are given in Table 1. The final strip thicknesses produced were in the range of about 1.0–1.5 mm, with the in-line hot rolling reductions ranging from 10 to 40%.

Tensile Properties — The average yield and tensile strength results for each trial niobium-microalloyed UCS steel are presented in Figure 4. The strength levels initially increased sharply for low levels of niobium, and thereafter progressively for niobium levels over about 0.02 wt. %. Overall, the results show that a 415 MPa UCS product can be achieved using a small addition of niobium, and a 450 MPa UCS product could be achieved with higher niobium levels. Thus, the addition of niobium to UCS steels substantially expanded the range of mechanical properties achievable from a similar carbon equivalent steel. In previous work, it was shown that strengthening in the niobium UCS product was primarily due to microstructural hardening; a predominantly bainite and acicular ferrite microstructure was...


Table 1  

Compositions of Niobium and Vanadium-Microalloyed Trial UCS Products, High Mn, 1020, and 1050 Grades (wt. %)

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Nb</th>
<th>V</th>
<th>N (ppm)</th>
</tr>
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<tbody>
<tr>
<td>Base</td>
<td>0.02-0.05</td>
<td>0.70-0.9</td>
<td>0.15-0.50</td>
<td>&lt; 0.003</td>
<td>&lt; 0.003</td>
<td>35-50</td>
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<tr>
<td>A</td>
<td>0.032</td>
<td>0.72</td>
<td>0.18</td>
<td>0.014</td>
<td>&lt; 0.003</td>
<td>78</td>
</tr>
<tr>
<td>B</td>
<td>0.029</td>
<td>0.73</td>
<td>0.18</td>
<td>0.024</td>
<td>&lt; 0.003</td>
<td>63</td>
</tr>
<tr>
<td>C</td>
<td>0.058</td>
<td>0.87</td>
<td>0.24</td>
<td>0.026</td>
<td>&lt; 0.003</td>
<td>76</td>
</tr>
<tr>
<td>D</td>
<td>0.050</td>
<td>0.85</td>
<td>0.21</td>
<td>0.041</td>
<td>&lt; 0.003</td>
<td>60</td>
</tr>
<tr>
<td>E</td>
<td>0.031</td>
<td>0.74</td>
<td>0.16</td>
<td>0.059</td>
<td>&lt; 0.003</td>
<td>85</td>
</tr>
<tr>
<td>F</td>
<td>0.030</td>
<td>0.86</td>
<td>0.26</td>
<td>0.065</td>
<td>&lt; 0.003</td>
<td>72</td>
</tr>
<tr>
<td>G</td>
<td>0.028</td>
<td>0.82</td>
<td>0.19</td>
<td>0.084</td>
<td>&lt; 0.003</td>
<td>85</td>
</tr>
<tr>
<td>H</td>
<td>0.025</td>
<td>0.92</td>
<td>0.22</td>
<td>&lt; 0.003</td>
<td>0.045</td>
<td>75</td>
</tr>
<tr>
<td>I</td>
<td>0.032</td>
<td>0.92</td>
<td>0.22</td>
<td>0.058</td>
<td>0.042</td>
<td>60</td>
</tr>
<tr>
<td>J</td>
<td>0.19</td>
<td>0.94</td>
<td>0.21</td>
<td>&lt; 0.003</td>
<td>&lt; 0.003</td>
<td>50</td>
</tr>
<tr>
<td>K</td>
<td>0.46</td>
<td>0.89</td>
<td>0.20</td>
<td>&lt; 0.003</td>
<td>&lt; 0.003</td>
<td>95</td>
</tr>
<tr>
<td>L</td>
<td>0.035</td>
<td>1.28</td>
<td>0.21</td>
<td>&lt; 0.003</td>
<td>&lt; 0.003</td>
<td>100</td>
</tr>
</tbody>
</table>

observed that was devoid of substantial grain boundary ferrite. Furthermore, transmission electron microscopy (TEM) examination of the microalloyed steels did not reveal any evidence of niobium precipitation.

The total elongation results are presented in Figure 4b, and it can be seen that the ductility continuously decreased as the yield strength increased. In particular, even at yield strength levels over 500 MPa, the total elongations were greater than 10%, which is a requirement for sheet steels for cold formed framing members, such as ASTM A1008 ST340H, for application in residential and commercial construction.

Age Hardening Heat Treatments — As noted earlier, TEM examination did not reveal any precipitation of Nb(CN) in the hot rolled condition. This indicates that niobium was held in solid solution and potentially available for age hardening in the niobium UCS steels. Laboratory age hardening heat treatments were undertaken and revealed a rapid age hardening response for the niobium grades. TEM examinations carried out on over-aged specimens found a uniform distribution of very fine precipitates in the size range of 6-15 nm, which were identified as being niobium-rich.

The age hardening response of niobium UCS steels observed in the short-time laboratory heat treatments (6- to 20-second holds at peak temperature) indicated the potential for age hardening in the steels using a continuous annealing line or the annealing section of a CGL. The processing temperature range seemed adequate, and the strength increment required could be controlled by the niobium content. Plant-scale trials have been conducted at the CGL at Auron’s Crawfordville plant to age harden the niobium UCS steels. The results from the full-scale production trials are summarized in Figure 5a for a range of the niobium UCS steels, and the results for an individual coil (steel C) are presented in Figure 5b. Significant and consistent strengthening was observed using the short heat treatment cycle on the hot-rolled continuous galvanizing line. The final strength levels recorded were similar to that produced with the laboratory heat treatments of the respective niobium UCS steels. Final strength levels of more than 550 MPa were recorded with the 0.024 wt. % niobium UCS (steel C), and more than 550 MPa with the higher niobium UCS steels (steel F and G). This outcome indicates the potential to further expand the range of UCS products to higher strengths and significantly increase the strength-thickness combinations possible for hot rolled structural strip grades.

With regard to ductility for the age hardened and galvanized niobium UCS product, the total elongation results are presented in Figure 6, compared to results for the as-rolled niobium UCS steels. The results highlight that, instead of an expected reduction of total elongation with increasing strength from age hardening, the total elongations were actually either similar or higher in the age hardened and galvanized condition, compared to the as-rolled UCS product. The microstructural changes that have produced this outcome are still under investigation.

Vanadium-Microalloyed UCS Steels — The composition of the trial steels microalloyed with vanadium and niobium is as outlined in Table 1. The variances and niobium levels for steels D and H were similar and both at the same level in steel E, at 0.04 wt. %, to allow the effect of each microalloying element to be assessed independently and in a dual microalloying system. For steel sheets, vanadium is typically employed in conjunction...
with nitrogen to facilitate the precipitation of VN to control properties. Recent work has demonstrated that effective strengthening can occur via association of individual vanadium and nitrogen atoms. As such, even in the absence of precipitation, some strengthening should be anticipated. While solute drag from vanadium is not typically expected to be as significant as with niobium, it is still of interest to determine if vanadium contributes to hardenability in U8H steel, given the attributes of large austenite grain sizes and acicular ferrite nucleation sites.

The Effect of Vanadium in Hot Rolled U8C Steels — The yield strength results for the 0.045 wt. % vanadium (steel H) are compared to the plain low-carbon base steel as a function of the hot rolling reduction in Figure 7. The yield strength results were within the range for the plain-carbon steel, indicating that the vanadium addition did not provide strengthening similar to niobium in the hot rolled condition. However, the tensile properties did indicate that the vanadium-microalloyed steel exhibited less sensitivity to the effect of hot rolling reduction on the final strength compared to the plain-carbon base steel. It should be noted that the range of hot rolling reductions applied to the vanadium-alloyed steel was limited.

The final microstructure of the 0.043 wt. % vanadium trial steel (steel H), shown in Figure 8a, was comprised of predominantly grain boundary ferrite and acicular ferrite, similar to the microstructure of the plain-carbon base steel produced with a similar cooling temperature. In contrast to niobium-microalloyed U8C, the 0.045 wt. % vanadium addition did not appear to have as much effect on the hardenability of the U8C steel. To highlight the hardenability potency of niobium, Figure 8b reveals that the formation of grain boundary ferrite was completely suppressed by a 0.024 wt. % niobium addition, resulting in a final microstructure comprised of bainite and acicular ferrite.

The yield strength results for the 0.043 wt. % vanadium U8C steel (steel H) were further compared to the results for the 0.041 wt. % niobium U8C steel (steel D) and the 0.088 wt. % niobium + 0.042 wt. % vanadium U8C steel (steel I) in Figure 9. It is clear from Figure 9 that:

- Higher strength levels were achieved with the 0.041 wt. % niobium than the 0.043 wt. % vanadium steel.
- The strength levels recorded for the 0.041 wt. % niobium steel and the 0.038 wt. % niobium + 0.042 wt. % vanadium steel were very similar.
- These results confirm that vanadium additions up to at least 0.04 wt. % did not provide strengthening of U8C steels comparable with niobium additions, produced by the Castrup process, in the hot rolled condition.

The Effect of Vanadium in Hot-Dip Galvanized U8C Steels — Age hardening heat treatments at 560°C and 780°C for 90 minutes were carried out on air-cooled strip samples of the 0.043 wt. % vanadium U8C steel (steel H) produced at a lower (500-600°C) and higher (600-700°C) cooling temperature. These heat treatments produced a substantial strength increase for both cooling temperature ranges (Figure 10). The strengthening increment was greater for the higher cooling temperature material, perhaps reflecting tempering of the predominantly acicular ferrite microstructure of the lower cooling temperature material, which offsets some of the age hardening strength increment. These results again highlight the capability of the Castrup process to retain microalloying elements in solid solution to provide substantial strengthening from subsequent aging heat treatments, as was shown previously for niobium-microalloyed U8C steels. However, the relatively low nitrogen levels for steels H and I may have limited the overall precipitation response in the vanadium system studied.

The laboratory age hardening results were confirmed in plant trials with the 0.045 wt. % vanadium-microalloyed U8C steel (steel H), in which the annealing section of a CGL has been utilized to apply an age hardening heat treatment (Table 2). A yield strength increase of about 50 MPa was realized, which approached the strength increase recorded from the laboratory age hardening heat treatments. The strength increase was also in the order of the strength increase achieved with the 0.041 wt. % niobium steel (steel D) processed with similar CGL conditions. The tensile property results for the 0.038 wt. % niobium + 0.042 wt. % vanadium U8C steel (steel I), similarly processed on a CGL, are also included in Table 2, as well as the typical tensile properties for the 0.041 wt. % niobium U8C steel (steel D), for comparative purposes.

It is notable from the tensile results in Table 2 that the niobium + vanadium U8C steel had a slightly higher strength than the 0.041 wt. % niobium steel in the hardened and galvanized condition. As both U8C steels had similar strengths in the as-hot rolled condition (Figure 9), these initial plant trial results indicate that the strengthening increment from age hardening the niobium + vanadium-microalloyed system is less than what would be realized if the strengthening increment was simply the cumulative increment from the individual microalloying elements.

Steels With Elevated Carbon Content

Hypereutectic carbon contents are of interest in the Castrup U8C product development plan for many applications. Carbon levels of 0.2 wt. % are of interest for structural applications where the use of microalloying is otherwise excluded from use. Higher carbon levels in the range of 0.3-0.5 wt. %, have many current applications for material in the thickness range of 1-9 mm. These include fasteners, structural components, and tools (scrapers,
Steel that is currently produced for these applications may require multiple annealing and cold rolling steps to achieve this thickness.

Hyperperitectic compositions exhibit a much broader temperature range for the mushy zone of liquid + solid than is the case in ≤0.05 wt. % carbon steel. Consequently, casting practices have to be tailored to address this difference in solidification behavior. The composition of the steels studied can be seen in Table 1 (steels J and K), and results are discussed below.

0.2% Carbon UCS Steel — The mechanical properties of the 0.2 wt. % carbon UCS steel are presented in Figure 11 as a function of the hot rolling reduction applied. The strength levels achieved were higher than that achieved with the current low-carbon steels. Yield strengths in excess of 380 MPa were recorded over the full range of hot reductions applied, while being processed with conventional cooling temperatures. This is in contrast to the behavior of the low-carbon (≤0.05 wt. % C) UCS steels, where lower cooling temperatures are applied to achieve yield strengths over 380 MPa, and then only for a limited range of hot reductions. This outcome reflects the higher hardenability of the 0.2 wt. % carbon UCS steel. However, the strength and total elongation levels achieved were still influenced by the degree of in-line hot reduction for the conventional cooling conditions applied for this trial. It can be inferred that the presence of carbon in this level is not sufficient to suppress recrystallization of the austenite as the strip is hot reduced.

The microstructures obtained in the 0.2 wt. % carbon UCS steels are shown in Figure 12. The final microstructure was a complex mixture of mainly acicular ferrite, with some fine pearlite and grain boundary ferrite plates (Figure 12a). The high proportion of acicular ferrite accounts for the high strength levels achieved. The proportion of acicular ferrite decreased and the proportions of pearlite and ferrite increased with increasing hot reduction (Figure 12b), which accounts for the lower strength levels recorded with increasing hot reduction.

0.5% Carbon UCS Steel — The tensile properties of the 0.5 wt. % carbon UCS steel, with as-hot rolled reductions of 20% (1.55 mm thick) and 5% (1.20 mm thick), are presented in Table 3. The tensile strengths recorded were over 800 MPa. Some examples of the microstructure obtained in the as-hot rolled condition are shown in Figure 13. It should be noted that all the coils of the 0.5 wt. % carbon steel produced were processed without water cooling being applied in the accelerated cooling section of the runout table (i.e., the strip was air cooled).

The microstructures, shown in Figure 13, contained very little polygonal ferrite. Thin, discontinuous networks of grain boundary ferrite, often associated with Widmanstätten ferrite, were present. The high level of hardenability imparted by this carbon content, and the minimal difference between A1 and A2, kept growth of the initial ferrite to a minimum. The bulk of the final microstructure consisted of lamellar pearlite that was very fine, identified using TEM thin foils. Measurements of interlamellar spacing between the plates ranged from ~50 to 150 mm. In addition to the pearlite, intragranular acicular ferrite was present, showing strong preferred orientation and a very thin lenticular structure.

For 0.5 wt. % carbon steel produced in the thickness range of 1.0–1.5 mm, they are typically provided as spheroidized annealed material. The mechanical properties obtained do not correspond with the typical mechanical properties seen in spheroidized 1050 steel. This is not unexpected, as the carbides that were present in the as-hot rolled strip, while very fine, are not spheroidite Fe₃C. At this time, the annealing response of U.S. material of compositions similar to steel K is being assessed.

The majority of current UCS steel is produced with a manganese content of 0.60–0.90 wt. %.

A batch of UCS steel (steel 1, from Table 1) was produced with a manganese content of 1.26 wt. %. The principle attribute of manganese is its contribution to the hardenability of steel. Increased hardenability provides two key benefits: (a) improved strength levels due to microstructural hardening and (b) macrostructural strengthening is maintained at higher hot reductions. This

<table>
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<tr>
<th>Steel</th>
<th>Condition</th>
<th>V.S.</th>
<th>T.S.</th>
<th>TE %</th>
<th>T.S./Y.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.043% V [steel I]</td>
<td>HR</td>
<td>593</td>
<td>403</td>
<td>20.6</td>
<td>1.25</td>
</tr>
<tr>
<td>0.043% V [steel II]</td>
<td>Galv</td>
<td>446</td>
<td>534</td>
<td>16.3</td>
<td>1.20</td>
</tr>
<tr>
<td>0.041% Nb [steel D]</td>
<td>Galv</td>
<td>516</td>
<td>596</td>
<td>16.0</td>
<td>1.15</td>
</tr>
<tr>
<td>0.05% Nb + 0.043% V [steel I]</td>
<td>Galv</td>
<td>550</td>
<td>625</td>
<td>16.1</td>
<td>1.18</td>
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**Table 3**

<table>
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<tr>
<th>Grade</th>
<th>Thickness</th>
<th>Y.S.</th>
<th>T.S.</th>
<th>TE %</th>
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<tr>
<td>0.5% C</td>
<td>1.55 mm</td>
<td>597</td>
<td>864</td>
<td>13.4</td>
</tr>
<tr>
<td>0.5% C</td>
<td>1.20 mm</td>
<td>607</td>
<td>897</td>
<td>13.4</td>
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</table>

**Figure 11**

Tensile properties as a function of hot rolling reduction for 0.2% UCS steel.

**Figure 12**

(a) Typical microstructures for 0.2% C grade with a rolling temperature of 600°C, where hot reductions were (a) 19% and (b) 57%.

**Figure 13**

(a) Typical microstructures for 0.5% C grade: (a) grain boundary ferrite and very fine lamellar pearlite and (b) intragranular acicular ferrite.
allows the production of thinner gauges (in this case at 0.9 mm) with the desired mechanical properties. This is illustrated in Figure 14, where the results for the 1.20 wt. % manganese UCS steel are presented as a function of the hot rolling reduction, in comparison with a current grade. The yield strengths realized for the 1.20 wt. % manganese UÇS steel were significantly higher than is typical of 0.6 wt. % manganese UÇS steel and exceeded 400 MPa, even for some hot rolling reductions greater than 40%.

Steels With Elevated Copper Content

Copper levels over about 0.20 wt. % are generally avoided in other sheet steel production methods due to concerns over hot shortness. In cases where copper levels are higher than 0.20 wt. % (such as in steels with improved atmospheric weathering resistance), expensive alloy additions such as niobium are commonly added to mitigate the risk of hot shortness. The Castrip process, however, has several features that minimize the potential for hot shortness. The key features are: the controlled atmosphere in the hot box, the brief interval between casting and rolling, and the very rapid solidification, which maintains copper in solution. These features will prevent the buildup of copper in the surface oxide layer that is generally required for hot shortness to occur. Due to the above-mentioned advantages, steel scrap that is higher in copper (used in facilities such as bar mills) can be employed for UÇS steel production without the potential for hot shortness. In anticipation of these types of scrap being employed, the effect of elevated copper levels (achieved through scrap selection) was investigated.

A substantial number of heats (> 30) with residual copper levels in the range of 0.2–0.4 wt. % have been produced for commercial consumption. These heats have not had any hot shortness reported, while nickel was not introduced as a countermeasure in any of these heats. Previously, a trial heat of about 0.6 wt. % copper had also been successfully cast without hot shortness being reported. This experience verifies the expectation that the Castrip process can successfully process high residual levels of copper without incurring hot shortness while also avoiding special practices or alloy additions. This also allows for the utilization of lower-cost scrap, thereby improving the cost of strip production via the Castrip process.

With respect to mechanical properties, the modest increase in hardenability provided by copper assisted with the achievement of the high-strength grades (yield strength of 380 MPa), which utilize high cooling rates and low cooling temperatures. For the low-strength grades, the low cooling rates and high cooling temperatures negate the effect of the increased copper content. Examples of tensile properties for a range of galvanized structural grades, covering varying manganese and cooling temperature, are presented in Table 4.

For hot-dip galvanized, high-residual copper UÇS, the base microstructure was not significantly altered as the CGL strip temperatures remained well below the A1 of the steel. Consequently, the mechanical properties of uncoated Cu-enriched UCS are similar to that for hot band substrate processed on a CGL.

Table 4

<table>
<thead>
<tr>
<th>Typical Properties of UÇS Grades With Copper Content at 0.2–0.4 wt. %</th>
<th>Mn level (wt. %)</th>
<th>Cooling temp. (°C)</th>
<th>Hot reduction</th>
<th>YS (MPa)</th>
<th>TS (MPa)</th>
<th>TS/YS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60–0.74</td>
<td>600–700</td>
<td>25–28%</td>
<td>331</td>
<td>428</td>
<td>25.6</td>
<td></td>
</tr>
<tr>
<td>0.60–0.74</td>
<td>500–600</td>
<td>15–20%</td>
<td>378</td>
<td>480</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td>0.80–0.85</td>
<td>500–600</td>
<td>20–25%</td>
<td>403</td>
<td>499</td>
<td>21.2</td>
<td></td>
</tr>
</tbody>
</table>

Be the best performing UÇS in the recovery annealed condition, as shown in Figure 15. The Castrip process also enables high-strength hot band to be readily produced from simple plain-carbon and Nb-microalloyed steels. This allows high-strength levels to be achieved in the recovery annealed condition with limited cold reduction. Finally, UÇS produced by the Castrip process has a high recrystallization temperature, attributable to the high manganese and silicon levels of UÇS steels and the presence of the very fine inclusions typical of Castrip UÇS. The combination of low cold reduction levels and a high recrystallization temperature allows relatively high recovery annealing temperatures to be applied, which aids the final ductility and provides a robust recovery annealing temperature range. A small niobium addition ( ~ 0.015 wt. %) further expands the recovery annealing temperature range and also enables advantage to be taken of age hardening, as discussed previously. The resultant tensile properties for 0.75-mm strip produced from plain-carbon and niobium-microalloyed UÇS steels in the recovery annealed condition are shown in Table 5. It is clear that ductility requirements for structural steels in the building codes were achieved (see Table 5 targets) at quite high strength levels. The niobium-microalloyed material has a higher strength while maintaining the ductility achieved in the plain-carbon substrates studied. Yield strengths in excess of 550 MPa were achieved, while still meeting the above-mentioned ductility requirements with small niobium addition. The results show the potential to realize a high-strength, light-gauge, coated strip product via the cold rolled and recovery annealed process route.
that offers sufficient ductility for cold formed structural steels by utilizing UCS products produced by the Gastrip process.

Summary
The work presented includes the initial exploration of opportunities for affecting the properties of UCS steel sheet produced via the Gastrip process. These include expanding on prior microalloying work by investigating the effect of vanadium, exploring the ability of the material to respond to recovery annealing, higher manganese contents, hyperperitectic carbon compositions, and the ability to produce strip products with residual copper levels that are either avoided or require expensive alloying to compensate for the raised copper levels. These will lead to many exciting new product opportunities for UCS strip. This work will also be beneficial as additional Gastrip facilities (such as the Nucon facility in Arkansas) start production.

References

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