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Recent developments with ultrathin cast strip products produced by the Castrip® 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
process, ultrathin, castrip®, developments, recent, produced, products, strip, cast

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

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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.[1–3] 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.[1–3]

This paper provides an update of the continuing progress on microalloying (use of niobium and/or vanadium), along with work related to other alloying options such as higher carbon contents (0.2–0.5 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.[4] 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.[1] These effects can be dramatic, as has been reported previously in the case of niobium additions.[3] 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.[5] 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 sheet 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.

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.

Ultrathin Cast Strip Production via the Castrip Process

Hot Rolled Strip — The details of the Castrip process have been reviewed elsewhere.[6–7] 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 shells 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

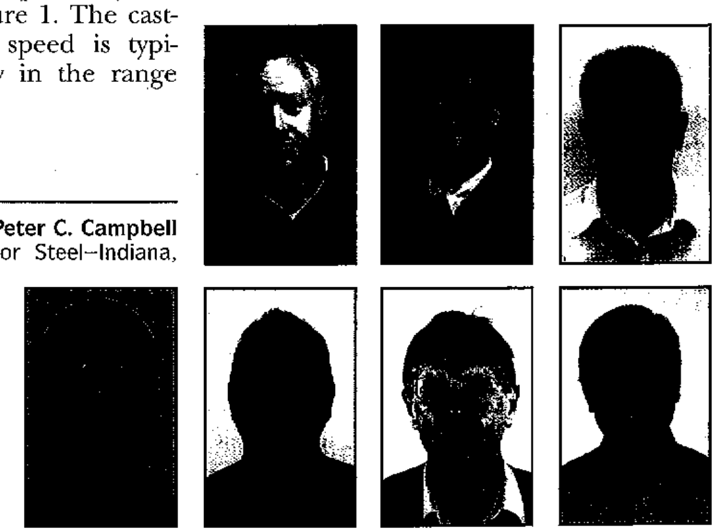

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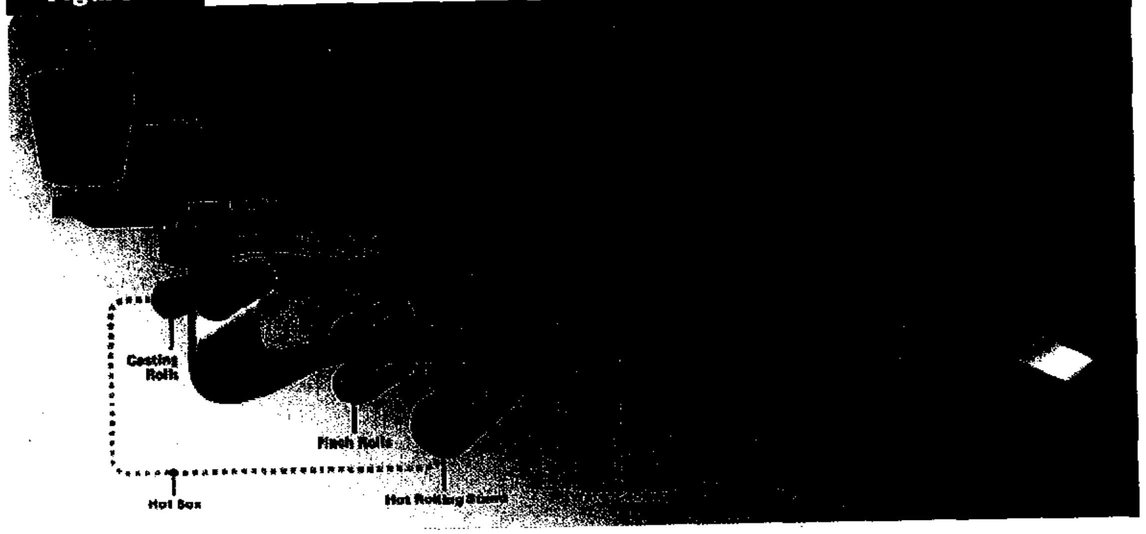
Figure 1



Main components of the Castrip process.

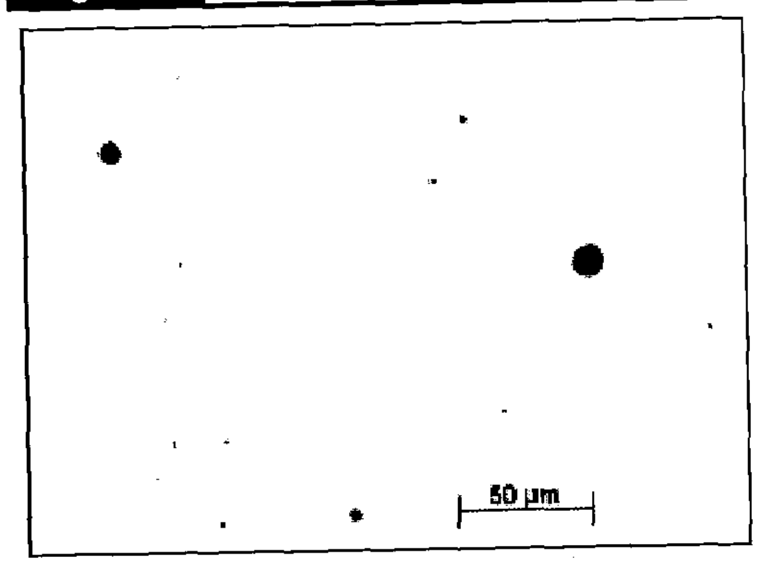
of 60–100 m/minute, and the as-cast strip thickness is typically 1.8 mm or less.

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 SiO_2 during the casting process to avoid clogging and to enhance the heat transfer rate to the casting rolls.[8] The rapid solidification rates possible with the strip casting process can, with control of certain parameters, promote a fine and 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 steel 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, therefore enhancing the performance of UCS product during subsequent forming, shearing or punching operations. In the Castrip process, the resultant inclusion/particle populations are tailored to achieve particle-stimulated, 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.[9–10] 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.[1,3] This austenite grain size is significantly larger than the austenite grain size produced in hot rolled strip at the exit of a conventional finishing mill. This coarse austenite grain size, in conjunction with the population of tailored inclusion/particles, assists with the particle-stimulated intragranular nucleation of acicular ferrite. A representative schematic illustration of the formation of acicular ferrite microstructures is shown in Figure 3.[11]

Figure 2



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

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 enhanced 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.

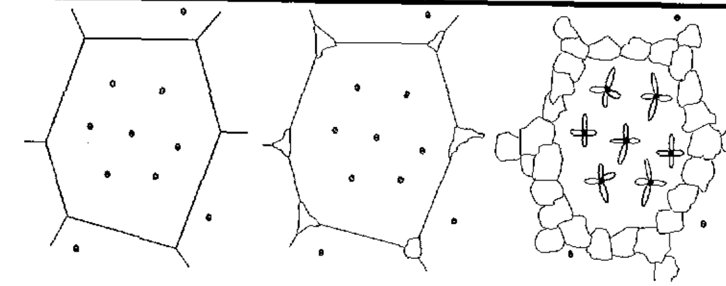
Hot-Dip Galvanized Strip — Galvanized UCS products are produced at Nucor Steel–Indiana utilizing a conventional continuous hot-dip galvanizing line (CGL). Coils are lap welded at the entry end to ensure continuous operation. The steel strip then proceeds through a cleaning section utilizing an alkali cleaner. The initial pre-heating 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 is then jet cooled to the pot immersion temperature (450–480°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 (G40 to G90 as described in ASTM A653). For the galvanized products discussed in this paper, aim 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 currently produced plain low-carbon steels provide a range of UCS products covering structural grades with yield strengths from 275 to 380 MPa. Higher-strength UCS products have recently been under development with yield strength levels up to 550 MPa using microalloying additions of niobium. The current range of plain low-carbon steels (base composition from Table 1) can be applied to achieve yield strength levels up to 380 MPa. However,

Figure 3



Schematic representation of the formation of acicular ferrite microstructures.[11]

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.[2]

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, as discussed above, particle-stimulated, intragranular nucleation of acicular ferrite in the niobium-microalloyed UCS steels can continue to represent a substantial portion of the microstructure.[3] The enhanced hardenability provided by niobium suppressed the formation of pro-eutectiod ferrite and promoted the formation of bainite.

A range of niobium-microalloyed steels have been successfully cast by the Castrip process with the niobium levels 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 4a. The strength level 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. %)

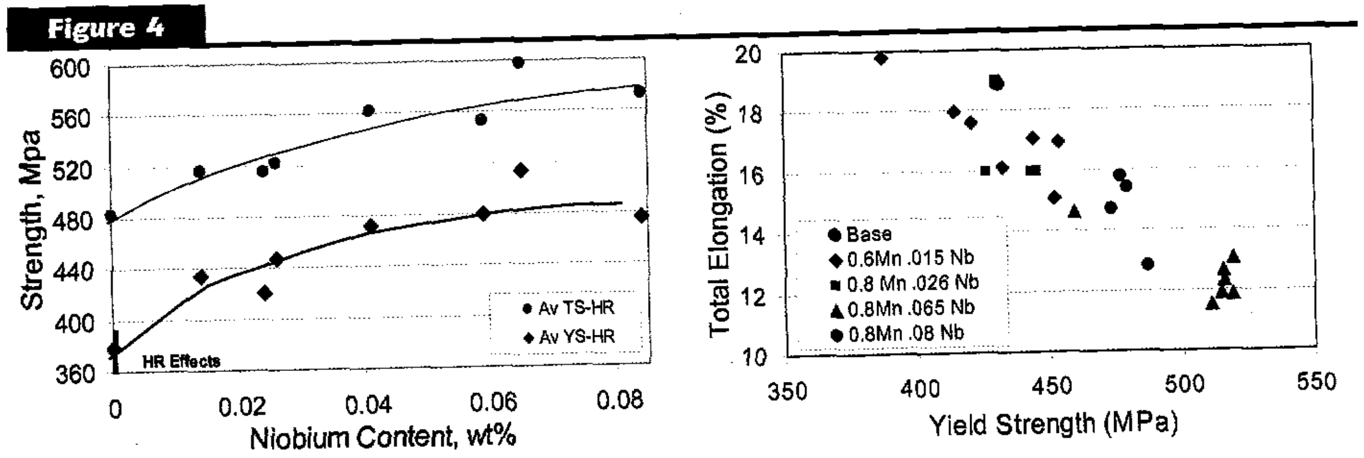
Steel	C	Mn	Si	Nb	V	N (ppm)
Base	0.02–0.05	0.7-0.9	0.15–0.30	< 0.003	< 0.003	35–90
A	0.032	0.72	0.18	0.014	< 0.003	78
B	0.029	0.73	0.18	0.024	< 0.003	63
C	0.038	0.87	0.24	0.026	< 0.003	76
D	0.032	0.85	0.21	0.041	< 0.003	65
E	0.031	0.74	0.16	0.059	< 0.003	85
F	0.030	0.86	0.26	0.065	< 0.003	72
G	0.028	0.82	0.19	0.084	< 0.003	85
H	0.025	0.92	0.22	< 0.003	0.043	75
I	0.032	0.92	0.22	0.038	0.042	60
J	0.19	0.94	0.21	< 0.003	< 0.003	85
K	0.46	0.89	0.20	< 0.003	< 0.003	95
L	0.033	1.28	0.21	< 0.003	< 0.003	< 100

observed that was devoid of substantial grain boundary ferrite.[3] 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. Importantly, 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 A1003 ST340H, for application in residential and commercial construction.

Age Hardening Heat Treatments — As noted earlier, TEM examination did not reveal any precipitation of Nb(C,N) 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.[3] TEM examinations carried out on over-aged

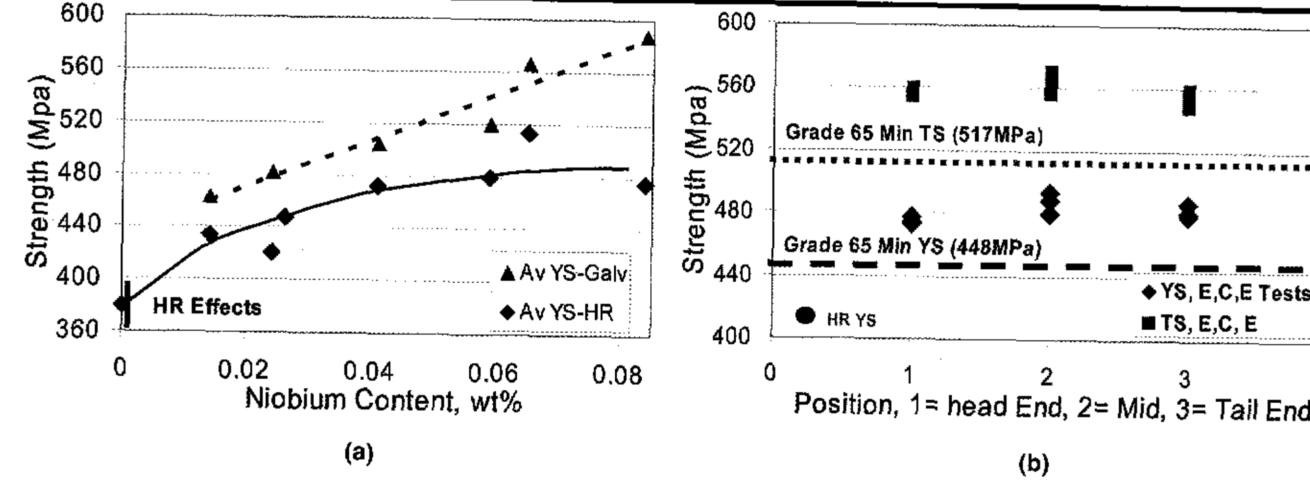
Figure 4



(a) (b)

(a) Effect of niobium content on the average yield strength and tensile strength of hot rolled Nb UCS steels; and (b) the change in total elongation with yield strength for the Nb-microalloyed UCS steels.

Figure 5



Age hardening response of Nb UCS steels observed after processing through a continuous hot-dip galvanizing line in terms of (a) effect on yield strength levels as a function of Nb content and (b) through coil yield and tensile strength variation for a coil of UCS steel C (0.024% Nb).

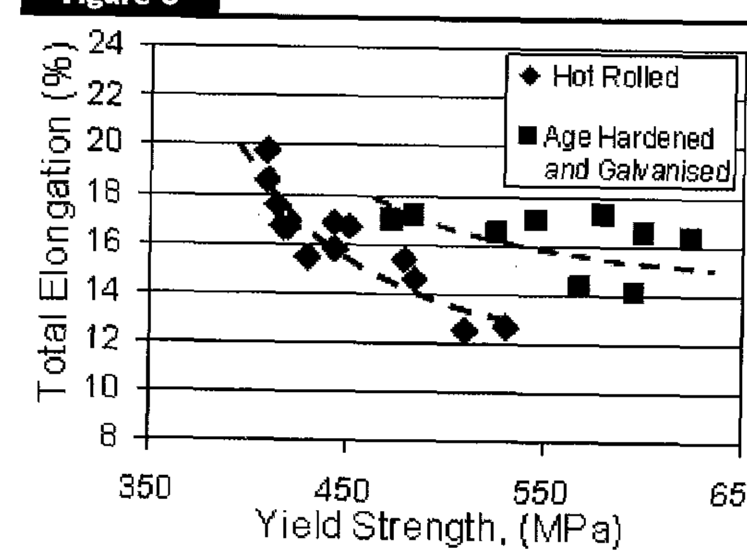
specimens found a uniform distribution of very fine precipitates in the size range of 4–15 nm, which were identified as being niobium-rich.

The age hardening response of niobium UCS steels observed in the short-time laboratory heat treatments (0- to 20-second holds at peak temperature) indicated the potential for age hardening these 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 on the CGL at Nucor's Crawfordsville 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-dip 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 450 MPa were recorded with the 0.024 wt. % niobium UCS steel (steel C), and more than 550 MPa with the higher niobium UCS steels (steels 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-hot 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-hot rolled UCS product. The microstructural changes that have produced this outcome are still under investigation.

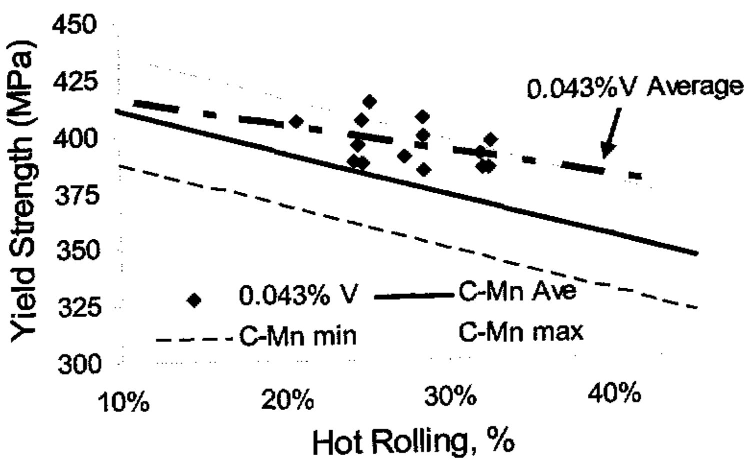
Vanadium-Microalloyed UCS Steels — The composition of the trial steels microalloyed with vanadium and niobium + vanadium are listed in Table 1. The vanadium and niobium levels for steels D and H were similar and both at the same level in steel I, at about 0.04 wt. %, to allow the effect of each microalloying element to be assessed individually and in a dual microalloying system. For steel sheets, vanadium is typically employed in conjunction

Figure 6



Comparison of total elongation results between hot rolled and age hardened and galvanized Nb-microalloyed UCS steels.

Figure 7



Yield strength results as a function of hot rolling reduction for the 0.043% V steel (steel H) and plain carbon steel base.

with nitrogen to facilitate the precipitation of VN to control properties.[12] Recent work has demonstrated that effective strengthening can occur via association of individual vanadium and nitrogen atoms.[13] 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 also of interest to determine if vanadium contributes to hardenability in UCS steel, given the attributes of large austenite grain sizes and acicular ferrite nucleation sites.[12]

The Effect of Vanadium in Hot Rolled UCS Steels — The yield strength results for the 0.043 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.

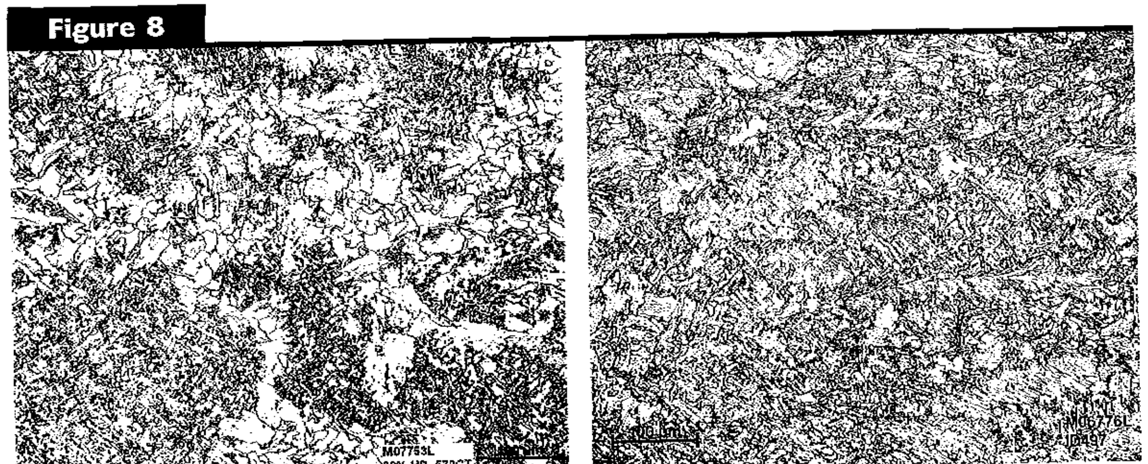
The final microstructure of the 0.043 wt. % vanadium trial steel (steel H), shown in Figure 8a, was comprised of predominately grain boundary ferrite and acicular ferrite, similar to the microstructure of the plain-carbon base steel produced with a similar coiling temperature. In contrast to niobium-microalloyed UCS, the 0.043 wt. % vanadium addition did not appear to have as much effect on the hardenability of the UCS 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 UCS steel (steel H) were further compared to the results for the 0.041 wt. % niobium UCS steel (steel D) and the 0.038 wt. % niobium + 0.042 wt. % vanadium UCS 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 UCS products comparable with niobium additions, produced by the Castrip process, in the hot rolled condition.

Figure 8



(a) (b)

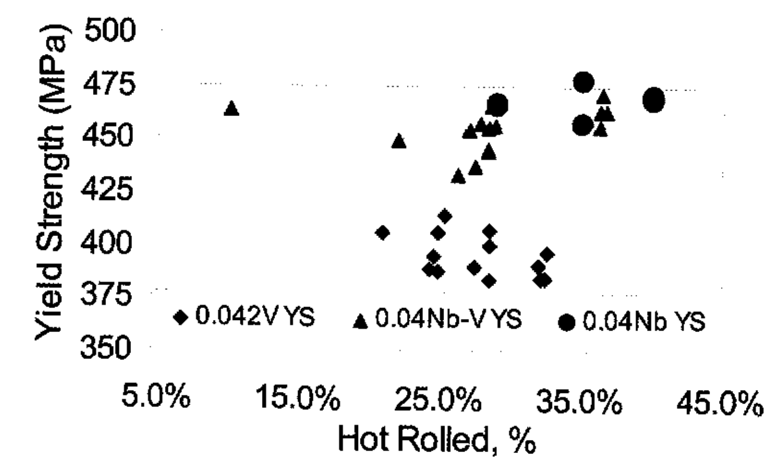
Microstructure of (a) 0.04% V grade compared to (b) 0.024% Nb grade, both coiled about 570°C; only the V grade displayed polygonal ferrite at prior austenite grain boundaries.

***The Effect of Vanadium in Hot-Dip Galvanized* UCS Steels** — Age hardening heat treatments at 650°C and 700°C for 20 minutes were carried out on as-hot rolled strip samples of the 0.043 wt. % vanadium UCS steel (steel H) produced at a lower (500–600°C) and higher (600–700°C) coiling temperature. These heat treatments produced a substantial strength increase for both cooling temperature ranges (Figure 10). The strength increment was greater for the higher cooling temperature material, perhaps reflecting tempering of the predominately acicular ferrite microstructure of the lower coiling temperature material, which offset some of the age hardening strength increment. These results again highlight the capability of the Castrip process to retain microalloying elements in solid solution to provide substantial strengthening from subsequent age hardening heat treatments, as was shown previously for niobium-microalloyed UCS steels.[3] 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 0.043 wt. % vanadium-microalloyed UCS 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% niobium steel (steel D) processed with similar CGL conditions.[3] The tensile property results for the 0.038 wt. % niobium + 0.042 wt. % vanadium UCS 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 UCS steel (steel D), for comparative purposes.

It is notable from the tensile results in Table 2 that the niobium + vanadium UCS steel had a slightly higher strength than the 0.041 wt. % niobium steel in the age hardened and galvanized condition. As both UCS 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 strength increment was simply the cumulative increment from the individual microalloying elements.

Figure 9

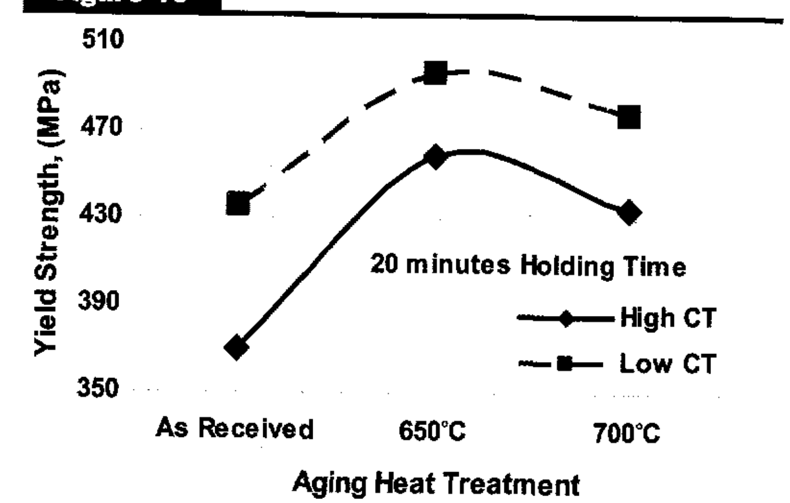


Yield strength results for the 0.043% V steel (steel H), 0.041% Nb steel (steel D) and the 0.038% Nb + 0.042% V steel (steel I).

Steels With Elevated Carbon Content

Hyperperitectic carbon contents are of interest in the Castrip UCS 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 1.0–1.5 mm. These include fasteners, structural components, and tools (scrapers,

Figure 10



Effect of age hardening heat treatments on the yield strength of the 0.043% V steel (Steel H) produced with two different coiling temperatures.

Table 2

Average Tensile Test Results, for the Longitudinal Direction, for Selected Galvanized Microalloyed Steels (MPa)

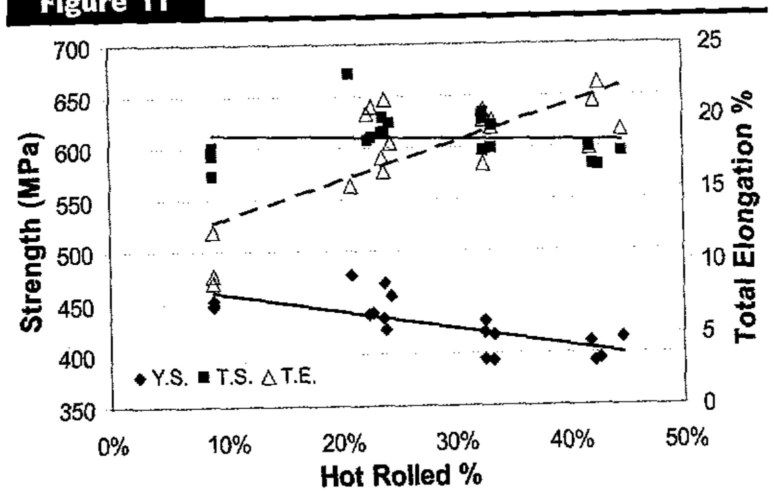
Steel	Condition	Y.S.	T.S.	T.E. %	T.S./Y.S.
0.043% V (steel H)	HR	393	493	20.6	1.25
0.043% V (steel H)	Galv	446	534	18.3	1.20
0.041% Nb (steel D)	Galv	518	596	16.9	1.15
0.038% Nb+0.042% V (steel I)	Galv	530	625	14.1	1.18

shovels, etc.). 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 heats 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 lower-carbon steels. Yield strengths in excess of 380 MPa were recorded over the full range of hot reductions applied, while being processed with conventional coiling temperatures. This is in contrast to the behavior of the low-carbon (≤ 0.05 wt. % C) UCS steels, where lower coiling temperatures are applied to achieve yield strengths over 380 MPa, and then only for a limited range of hot reductions.[3] 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 at this level is not sufficient to suppress recrystallization of the austenite as the strip is hot reduced.

Figure 11



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

The microstructures obtained in the 0.2 wt. % carbon UCS steel are shown in Figure 12. The final microstructure was a complex mixture of mainly acicular ferrite, with very 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 slightly 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 26% (1.33 mm thick) and 34% (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 A_3 and A_1, kept growth of any 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 nm. In addition to the pearlite, intragranular acicular ferrite was present, showing strong, preferred orientation and a very thin lenticular structure.

Figure 12

(a) (b)

Typical microstructures for 0.2% C grade with a coiling temperature of 600°C, where hot reductions were (a) 19% and (b) 37%.

For 0.5 wt. % carbon steels produced in the thickness range of 1.0–1.5 mm, they are typically provided as spherodized annealed material. The mechanical properties obtained do not correspond with the typical mechanical properties seen in spherodized 1050 steel.[14] This is not unanticipated, as the carbides that were present in the as-hot rolled strip, while very fine, are not spherodite Fe_3C. At this time, the annealing response of UCS material of compositions similar to steel K is being assessed.

Steels With Elevated Manganese Content

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

Table 3

Typical Properties of 0.5% C UCS steel (MPa)

Grade	Thickness	Y.S.	T.S.	T.E. %
0.5% C	1.33 mm	597	884	13.4
0.5% C	1.20 mm	607	897	13.4

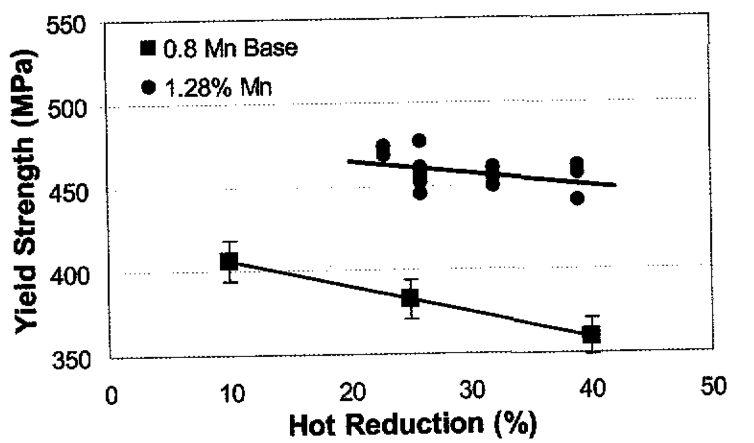
A batch of UCS steel (steel L from Table 1) was produced with a manganese content of 1.28 wt. %. The principle attribute of manganese of interest is its contribution to the hardenability of steel.[4] Increased hardenability provides two key benefits: (a) improved strength levels due to microstructural hardening and (b) microstructural strengthening is maintained at higher hot reductions. This

Figure 13

(a) (b)

Typical microstructures for 0.5% C grade: (a) grain boundary ferrite and very fine laminar pearlite and (b) intragranular acicular ferrite.

Figure 14



Yield strength as a function of the hot rolling reduction for a 1.28% Mn steel compared to a current base grade.

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 1.28 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 1.28 wt. % manganese UCS steel were significantly higher than is typical of 0.8 wt. % manganese UCS steel and exceeded 440 MPa, even for in-line 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.[15] 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 nickel 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.[16] Due to the above-mentioned advantages, steel scrap that is higher in copper (used in facilities such as bar mills) can be employed for UCS 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 (> 20) 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 higher-strength grades (yield strength of 380 MPa), which utilize high cooling rates and low coiling temperatures. For the lower-strength grades, the low cooling rates and high coiling temperatures negated the effect of the increased copper content. Examples of tensile properties for a range of galvanized structural grades, covering varying manganese and coiling temperatures, are presented in Table 4.

For hot-dip galvanized, high-residual copper UCS, the base microstructure was not significantly altered, as the CGL strip temperatures remained well below the A_{c1} 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

Typical Properties of UCS Grades With Copper Content at 0.2–0.4 wt. %

Mn level (wt. %)	Coiling temp. (°C)	Hot reduction	YS (MPa)	TS (MPa)	TE (%)
0.68–0.74	600–700	23–28%	321	428	26.0
0.68–0.74	500–600	15–20%	378	480	22.7
0.80–0.85	500–600	20–26%	403	499	21.2

Development of a Light-Gauge, Recovery Annealed High-Strength Coated UCS

Steels for certain cold formed structural sections, such as those used in residential framing, require the dual ductility requirement of a minimum total elongation of 10% and a minimum TS-to-YS ratio of 1.08. For coated steel with strip thicknesses less than about 1.6 mm, it is very challenging to achieve high strength levels and meet these ductility requirements. Specifically, these ductility requirements prohibit the use of full hard cold rolled material. To achieve these requirements for coated cold rolled material, very expensive alloying options generally need to be considered.

For coated sheet products in the range of about 0.9–1.5 mm, high strength levels with excellent ductility can be achieved using niobium-microalloyed UCS produced by the Castrip process and subsequently age hardened during continuous hot-dip galvanizing, as previously discussed.[3] For coated sheet thicknesses in the range of about 0.7–0.9 mm, a cold rolled and recovery annealed product has been under development.

There are several attributes of UCS produced by the Castrip process that provide the potential to manufacture coated, high-strength products that achieve the ductility requirements discussed above via a cold rolled and recovery annealed process route. The thin hot band thicknesses produced by the Castrip process enable low levels of cold reduction to achieve the final thickness required. Restricting the cold reduction improves the final recovery annealed ductility, 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, UCS produced by the Castrip process has a high recrystallization temperature, attributable to the high manganese and silicon levels of UCS steels and the presence of the very fine inclusions typical of Castrip UCS. 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.[3]

The resultant tensile properties for 0.75-mm strip produced from plain-carbon and niobium-microalloyed UCS 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 the 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

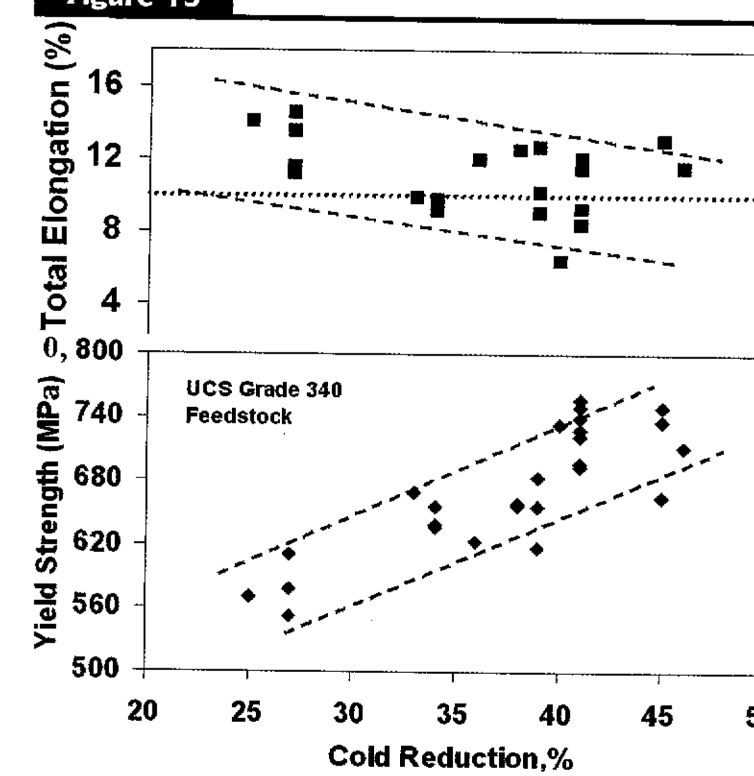
Table 5

Average Tensile Properties for C-Mn and 0.015 wt. % Niobium UCS Steels in the Recovery Annealed Condition (Thickness 0.75 mm)

Grade	YS, MPa	TS, MPa	T.S./Y.S.	T.E., %
C-Mn #1	549.1	606.3	1.11	14.2
C-Mn #2	530.5	581.5	1.11	14.4
0.015% Nb	593.2	650.4	1.10	13.1
Target	≥ 490	*	≥ 1.08	≥ 10

* = minimum tensile strength dependant on produced yield strength.

Figure 15



Effect of cold reduction on strength and ductility of galvanized UCS in the recovery annealed condition.

that offers sufficient ductility for cold formed structural steels by utilizing UCS products produced by the Castrip process.

Summary

The work presented includes the initial exploration of opportunities for affecting the properties of UCS steel sheet produced via the Castrip process. These include expanding on prior microalloying work by investigating the effect of vanadium, exploring the ability of the material to respond via 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 Castrip facilities (such as the Nucor facility in Arkansas) start production.

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