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By
R. Nooning, Jr., D. Edelman & P. Campbell – Nucor Steel Indiana
C. R. Killmore, H. Kaul, A. Phillips & J. G. Williams – BlueScope Steel

17 July 2007

1915 Rexford Rd., Ste 150, Charlotte NC 28211
USA
Telephone: 704.972.1820
Facsimile: 704.972.1829

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R. Nooning Jr. [1], C.R. Killmore[2], H. Kaul[2], A Phillips[2], D. Edelman[1], P. Campbell[1], J.G. Williams[2]

[1]Nucor Steel - Indiana,
4537 South Nucor Road,
Crawfordsville, Indiana, 47933, USA.
Tel: 765 364 1323
Fax: 765 361 5733
E-mail: bnooning@ns-ind.com; dedelman@ns-ind.com, pcampbell@ns-ind.com

[2]Metallurgical Technology, BlueScope Steel,
Five Islands Rd
Port Kembla, NSW, 2500, Australia.
Tel: 61 2 42757522
Fax: 61 2 42753489
E-mail: chris.killmore@bluescopesteel.com; andrew.phillips@bluesopesteel.com; harold.kaul@bluescopesteel.com; jim.williams@bluescopesteel.com

Keywords: Direct Strip Casting, UCS, Ultra-Thin Cast Strip, Acicular Ferrite, Mechanical Properties, Micro-Alloying

INTRODUCTION

The CASTRIP® facility at Nucor Steel's Crawfordsville, Indiana plant is the world's first commercial installation for production of Ultra-Thin Cast Strip (UCS), via twin-roll strip casting[1]. The CASTRIP process has been described in detail elsewhere[2, 3, 4, 5]. The facility has been producing plain, low-carbon sheet steel since its start-up in 2002. Strip thicknesses in the range of 0.9mm to 1.5mm have been in regular production, thereby extending the strip thickness range for hot rolled strip products and allowing substitution for cold rolled strip products. A number of commercial and structural grades are in regular production, with typical strength levels up to ASTM A1011M SS Grade 380 MPa (55 ksi) (referred to hereafter as Grade 380).

While the initial focus has been on developing a range of grades up to ASTM A1011M SS Grade 340 (50 ksi) (referred to hereafter as Grade 340), more recent development effort has been directed at capitalizing on the ability of the CASTRIP process to readily produce thin high-strength strip with minimum yield strengths from 380 MPa (55 ksi) to over 550 MPa (80 ksi). Such product development will extend the availability of high strength hot rolled grades into strip thicknesses that are not readily produced by conventional hot rolling mills. Several approaches have been adopted to reach the higher strength levels, including the use of microalloying, and each of them will be discussed.

The availability of thin UCS hot band also provides the potential to further extend the thickness range for high strength structural quality grades to less than 0.9 mm (0.035 in.) by utilizing cold rolling and recovery annealing. Through minimal amounts of cold rolling followed by recovery annealing, the potential for high-strength, thin gauge sheet is made possible. Some initial results from trials utilizing the recovery annealing processing route are presented.

THE CASTRIP PROCESS

The CASTRIP process, similar to all twin-roll casting operations, utilizes two counter rotating rolls to solidify two individual shells that are subsequently formed into a continuous sheet at the roll nip. The main components of the CASTRIP facilities at Nucor Steel Crawfordsville are depicted in Fig. 1. The ladle size used is 110 metric tons, which feeds a large conventional tundish and then a smaller tundish or transition piece. The transition piece is designed to reduce the ferrostatic head of the liquid steel as well as distribute the metal flow across the barrel length of the casting rolls. The core nozzle sits between the casting rolls, immersed in the metal pool, to finally deliver liquid metal to the metal pool. The speed of casting is typically in the range of 60-100 m/min (180 to 300 ft/min) and the as-cast strip thickness is typically 1.7mm or less. In order to limit scale growth on the strip surface a controlled atmosphere is maintained through the use of a 'hot box', which contains the strip until entry into the hot rolling stand. The in-line hot rolling mill is capable of 50% hot reduction, with reduction levels up to 45% regularly applied. The water cooling facility, located immediately after the rolling stand, cools the strip through the austenite to ferrite transformation to achieve the required coiling temperature. Two down coilers at the end of the process allow continuous operation of the casting process.

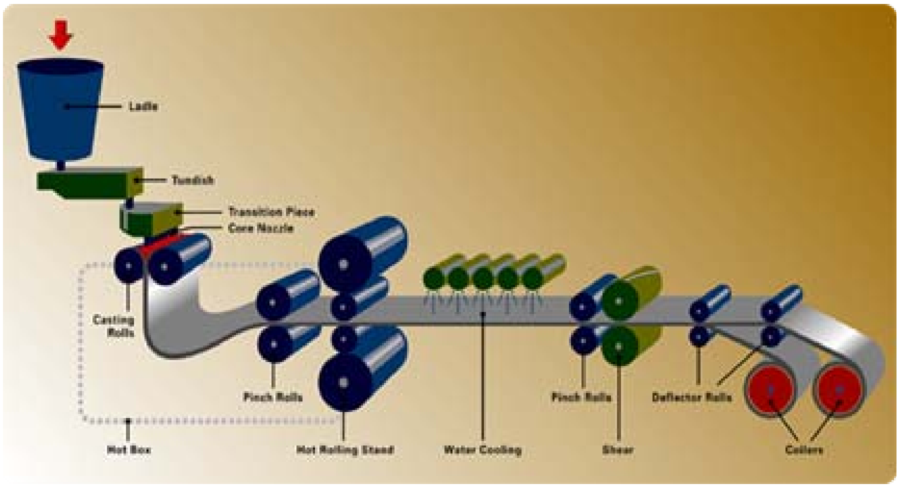


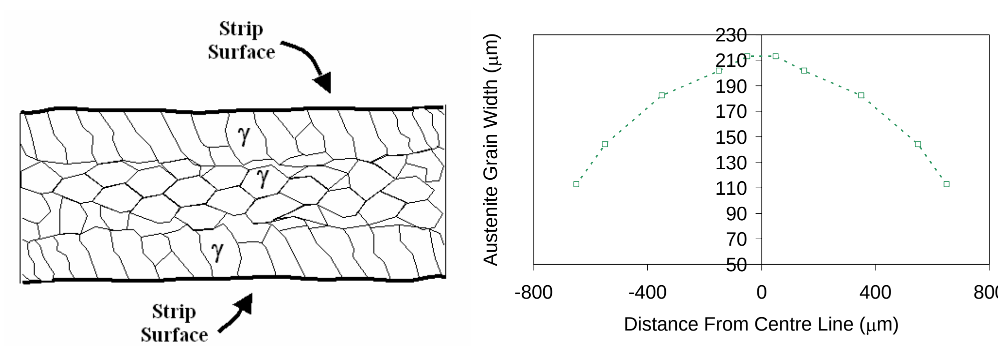
Figure 1. Main components of the CASTRIP process.

The primary steel composition used for the current grades in production is a low carbon (<0.05 wt%) - 0.6 wt% manganese - 0.2 wt% silicon steel. Throughout this paper, this steel composition will be referred to as the base composition or 0.6 Mn. This alloy design was adopted to ensure the deoxidation products of MnO and SiO_2 are liquid during the casting process to avoid clogging and to enhance the heat transfer rate. Although this inclusion engineering practice results in a higher volume fraction of non-metallic inclusions compared to conventionally processed Al-fully killed steel, 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 through the strip thickness. Moreover, in contrast to strip produced from conventional slab casting processes, the limited in-line hot rolling reductions do not significantly elongate the inclusions, so that they are not necessarily harmful to formability and shearing[6].

MICROSTRUCTURAL DEVELOPMENT

As-Cast Structure

The as-cast prior austenite grain structure of UCS steels typically consists of elongated grains extending from the surface towards the center of the strip with equiaxed grains in the center. These austenite grains are about 200 µm wide and 450 µm long. A schematic representation of the as-cast austenite grain structure is shown below in Fig. 2. The grains in the center of the strip are generally larger than those near the surface of the strip due to the decreased cooling rate during solidification. The profile of the austenite grain size across the strip thickness is shown in Fig. 2 (b).



(a) (b)

Figure 2. (a) Schematic illustration of the as-cast austenite grain structure of the UCS strip and (b) the austenite grain size through the thickness of the as-cast UCS strip.

Effect of Hot Rolling

The CASTRIP facility in Crawfordsville, Indiana is equipped with a single-stand hot mill capable of reductions up to 50%. Since the cast gauge varies by only about 10% (typically 1.58 to 1.75 mm or 0.062 to 0.069 in.), the degree of hot reduction is primarily a function of the ordered gauge, where the lighter the ordered gauge, the higher the hot rolling reduction. Hot reductions are kept above 10% for improved gauge control. As indicated in Fig. 3, at low amounts of hot reduction (3% and 13% in the graph) the austenite grain structure recrystallizes near the surface causing a refinement of the average austenite grain size in this location. The near surface region of the strip is preferentially affected because this is where the rolling strains are concentrated. With increasing hot reduction (22% and 29% in Fig 3.), recrystallization of the austenite grains extends to the center of the sheet as evidenced by the reduction in austenite grain size. Recrystallization of the as-cast austenite grains through the full strip thickness is achieved at around 30% hot reduction. For a fully recrystallized strip, the final austenite grain size averages around 60 µm, less than half of the original as-cast grain size that averaged around 160 µm. As shown below in Fig. 4 for the example of hot rolled galvanized UCS Grade 340, the effect of hot reduction on the austenite grain size has a large effect on the ability to make high strength product. The reasons for this will be elaborated in the following section.

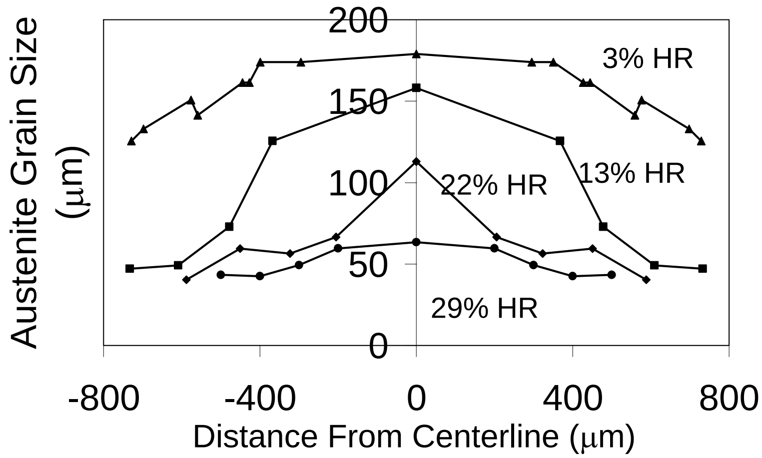


Figure 3. Effect of hot rolling on the austenite grain size and variability through the thickness of a UCS strip (base composition).

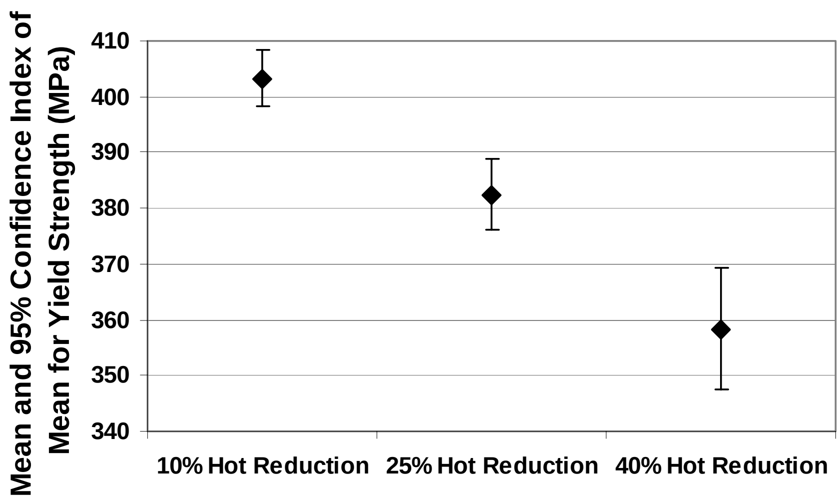


Figure 4. Production data for hot rolled galvanized UCS Grade 340 product showing the effect of hot reduction on yield strength.

Effect of Cooling Rate

The cooling profile during the transformation of austenite to the final microstructure is controlled by water sprays located immediately after the hot rolling mill. For a given chemistry, the final microstructure and corresponding strength level are controlled primarily by the extent of hot reduction and the cooling rate. In this section, four conditions will be described for the example of the base chemistry; low hot reduction with slow cooling, low hot reduction with rapid cooling, high hot reduction with slow cooling, and high hot reduction with rapid cooling.

As discussed previously, for small hot reductions (<15%), a coarse unrecrystallized austenite grain size similar to the as-cast austenite grain structure is retained. With this austenite microstructure, a slow cooling rate results in predominantly pro-eutectoid ferrite with some intragranular acicular ferrite. This microstructure achieves yield strengths in the 275-340 MPa (40-50 ksi) range. A higher cooling rate with the same prior austenite microstructure results in a higher proportion of intragranular acicular ferrite with less grain boundary ferrite and accordingly higher strength. This combination of a high cooling rate combined with minimal hot reductions provides the highest strength product utilizing the base composition, with typical yield strengths in the 340-410 MPa (50-60 ksi) range.

As shown previously, large hot reductions (>25 %) result in recrystallization of the austenite and a much finer austenite grain size compared to the as-cast austenite grain structure. The finer austenite grain structure decreases the hardenability of the steel by increasing the density of nucleation points for grain boundary ferrite. Even at the highest cooling rates currently possible (80-100°C/second) on the CASTRIP plant, the final product contains a significant amount of grain boundary and polygonal ferrite due to the lower hardenability of the fine grained prior austenite. The resulting mix of grain boundary ferrite and intragranular acicular ferrite resulting from high hot reductions and rapid cooling provides typical yield strengths from 310 to 380 MPa (45-55 ksi), which is 35-70 MPa (5-10 ksi) lower than the low hot rolling reduction condition using the same cooling rate. This is demonstrated above in Fig 4. While the finer austenite grain structure typical of high hot reductions causes difficulties making high strength product with the base composition, it provides opportunities for making a lower strength product. Using a slow cooling rate with the high reductions provides the softest product possible, as this provides the largest proportion of equiaxed ferrite with minimal intragranular acicular ferrite. Typical yield strengths for this microstructure are in the 240-310 MPa (35-45 ksi) range. The final microstructure and related strength levels for the various combinations of hot rolling reductions and cooling rates are shown below in Fig. 5.

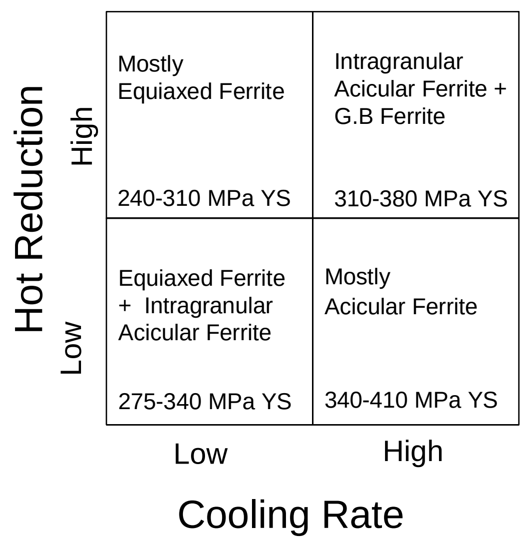


Figure 5. Combined effect of hot reduction and cooling rate on microstructure and strength levels for UCS Steels, base chemistry.

HIGH STRENGTH DEVELOPMENT

The base steel composition allows for production of strength levels from ASTM A1011M Grade CS-B up to Grade 340. To expand the product mix, a program was undertaken with the goal to produce three new UCS grades via the CASTRIP process; ASTM SS Grades 380 (55ksi), 480 (70 ksi) and Grade 550 (80 ksi). The ASTM A1011M specification for these grades in gauges less than 0.65 mm (0.064") indicates minimum total elongations (at a 50mm gauge length) of 9%, 7%, and 6% percent respectively. However, building codes (ASTM A1003) for the use of light-gauge steel in residential and commercial construction specify a minimum of 10% elongation for many applications. Therefore, a critical goal for the each of these grades is to develop new UCS steels with the required yield strengths while maintaining a total elongation greater than 10%.

Increased Alloying

To consistently achieve Grade 380 properties, a higher Mn grade has been developed. The Mn level was increased from 0.6 wt% Mn to 0.8 wt% Mn. At slow cooling rates the increased Mn shows little effect on the tensile properties of the base composition (Fig. 6); however at higher cooling rates and lower coiling temperatures, the higher Mn level substantially increases the yield strength. The higher strength reflects a higher proportion of acicular ferrite in the final microstructure, which can be attributed to an increase in hardenabililty provided by the higher Mn level. At higher cooling rates, the strength level increases by 5-10 ksi, which provides for a reliable Grade 380 product. However, at lighter gauges the reduced austenite grain size, resulting from the higher hot rolling reduction, produces an increase in the amount of grain boundary ferrite and a corresponding decrease in strength (Fig. 7). Therefore, while the high Mn chemistry can provide the strength levels necessary for Grade 380 produced with low levels of hot reduction, a different approach is necessary to produce this grade where high levels of hot reduction are needed to achieve the required final thickness.

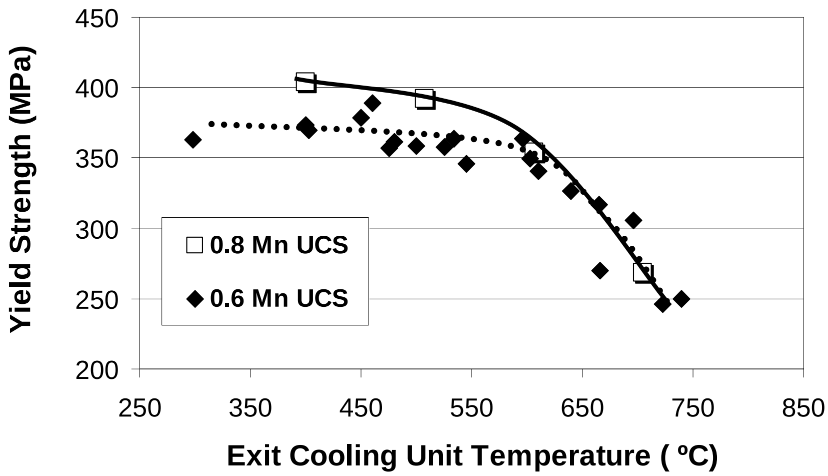


Figure 6. Effect of run out table cooling conditions on the yield strength of UCS Steels.

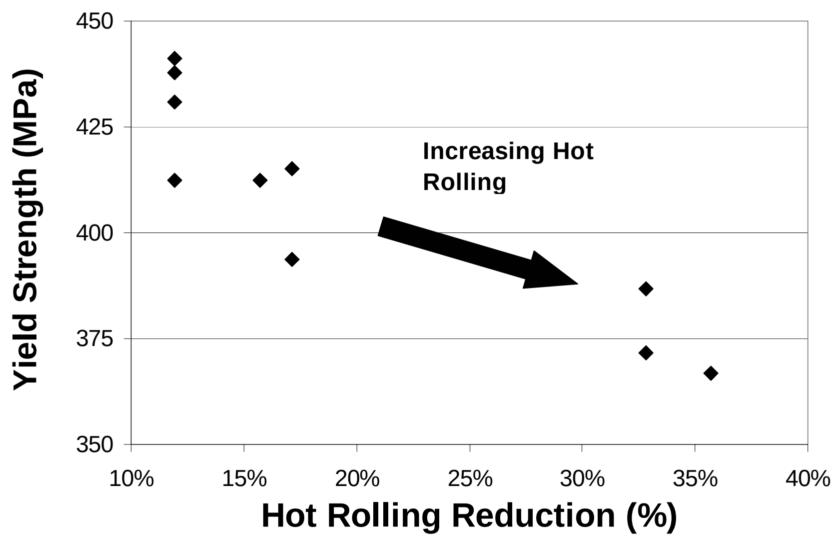


Figure 7. Effect of hot reduction on yield strength, 0.8 Mn Steel, 480°C (900°F) coiling temperature.

Temper Rolling

One approach to produce higher strength product is to utilize temper rolling of the UCS hot band. Temper rolling is an attractive option for two reasons. First, the ability of the CASTRIP process to produce hot band in the gauges previously only available as cold rolled allows for the production of light-gauge temper rolled material without prior cold rolling and annealing. Second, temper rolling is a relatively inexpensive method to try and achieve these properties.

Starting with a 1.5 mm (0.060 in.) thickness, 0.8% Mn Grade 380 hot band, several samples were temper rolled in the laboratory from 0.5 up to 20%. Similarly, 0.8% Mn Grade 380 hot band was temper rolled 3%, 5%, and 7% at the Nucor-Crawfordsville temper rolling facility. The results of the laboratory work agreed well with the production data as shown in Fig. 8. These results indicate that a 480 MPa yield strength in combination with 10% total elongation is possible via temper rolling, using a 0.8% Mn composition as feedstock. Figure 8 also shows that while higher strength levels were achieved, elongations dipped below 10% at strength levels greater than 525 MPa.

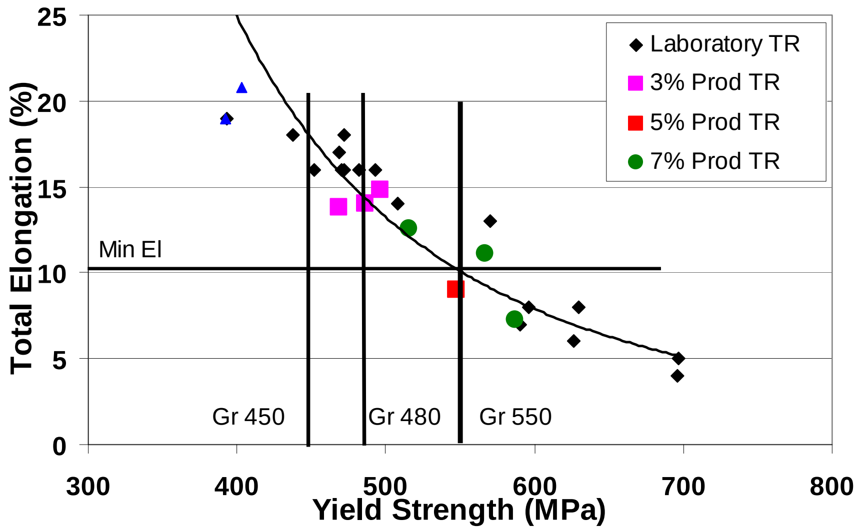


Figure 8. Effect of temper rolling on the yield strength and elongation for a Grade 380 UCS hot band.

Recovery Annealing

Another way to take advantage of the light-gauge hot band produced by the CASTRIP process is to use recovery annealing following cold rolling to produce a high-strength light-gauge product with enhanced ductility. UCS material produced by the CASTRIP process exhibits a higher recrystallization temperature than conventional Al-killed, plain, low-carbon strip steel due to its' higher alloy content and the presence of a very fine oxide particle distribution[7,8,6]. By using light-gauge UCS material for feedstock, low levels of cold reduction can be applied as compared to conventional recovery annealed steels, further increasing the recrystallization temperature. The combination of these factors provides UCS material, produced via the CASTRIP process, with an expanded temperature range for recovery annealing compared to conventional low-carbon, cold rolled strip. The result is the ability to achieve reasonable levels of ductility in conjunction with high strength levels after recovery annealing.

Initial laboratory studies were conducted using the base composition at two different strength levels, Grade 275 and Grade 340. The samples were laboratory cold rolled from 10% to 50% and then annealed, simulating the conditions in the galvanizing line at Nucor-Crawfordsville. The peak metal temperature was varied from 500 to 850°C (930 to 1560°F). Resulting yield strength versus peak metal temperature and yield strength versus elongation for the Grade 340 base composition are shown below in Figs. 9 and 10.

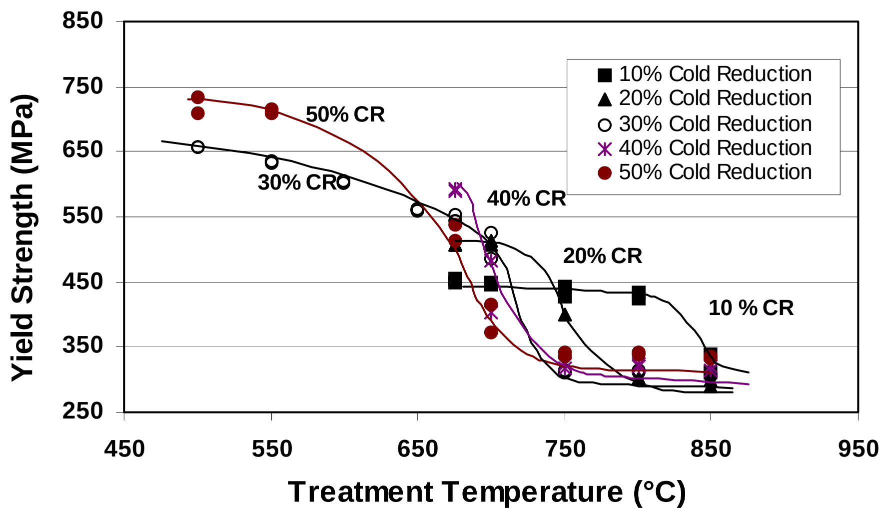


Figure 9. Yield strength vs. peak annealing temperature for recovery annealed UCS material, Grade 340 feedstock.

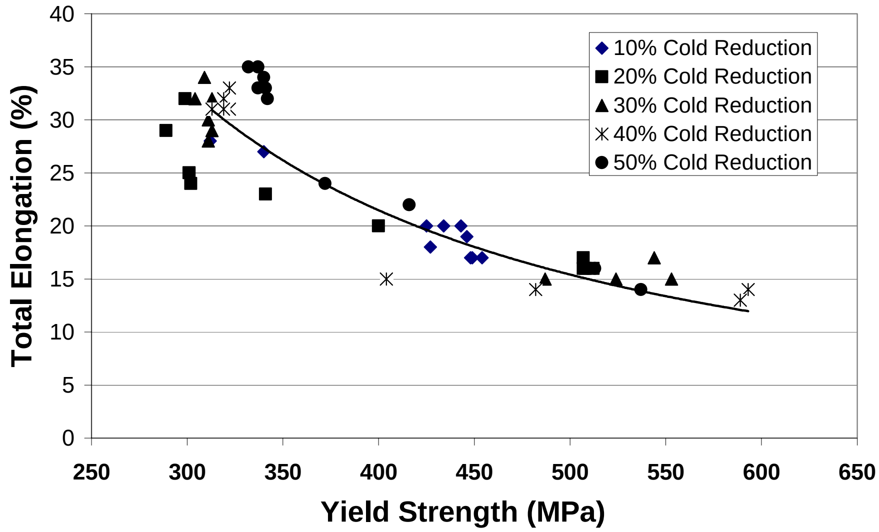


Figure 10. Elongation vs. strength curves for recovery annealed UCS material, Grade 340 feedstock.

The laboratory studies demonstrated the potential for a Grade 480 or even Grade 550 light-gauge, galvanized product via recovery annealing. Subsequently full-scale mill trials were designed based upon the laboratory results and were carried out using Grade 340 UCS material as feedstock. The yield strength and ductility levels achieved after recovery annealing and galvanizing are shown in Fig. 11, as a function of prior cold reduction. It can be seen that for cold reduction levels below about 30%, total elongations in excess of 10% were achieved in combination with yield strengths well in excess of 480 MPa. More laboratory and plant trials are currently ongoing to further refine the processing variables. In particular, the effects of composition, coiling temperature, hot and cold reduction as well as annealing temperature are being assessed.

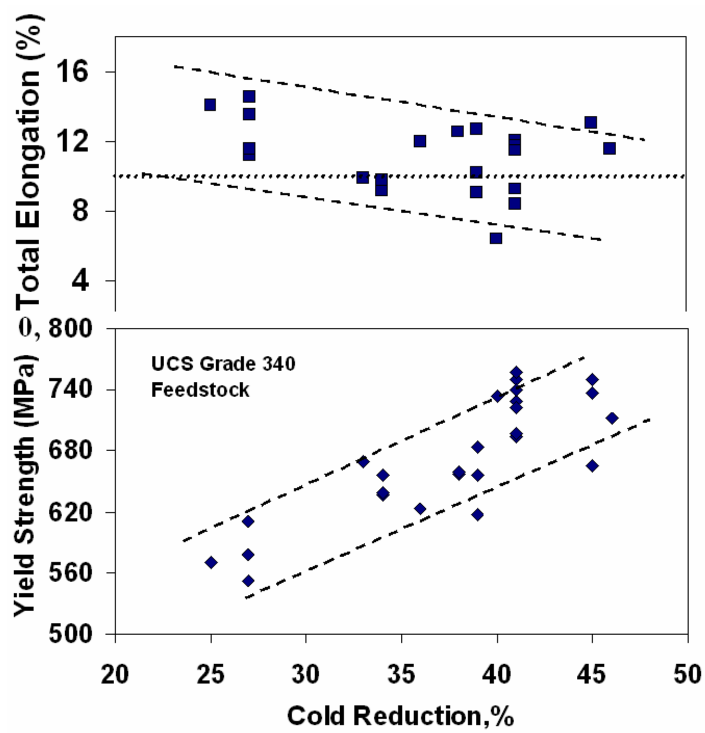


Figure 11. Results of recovery annealing plant trials using Grade 340 feedstock.

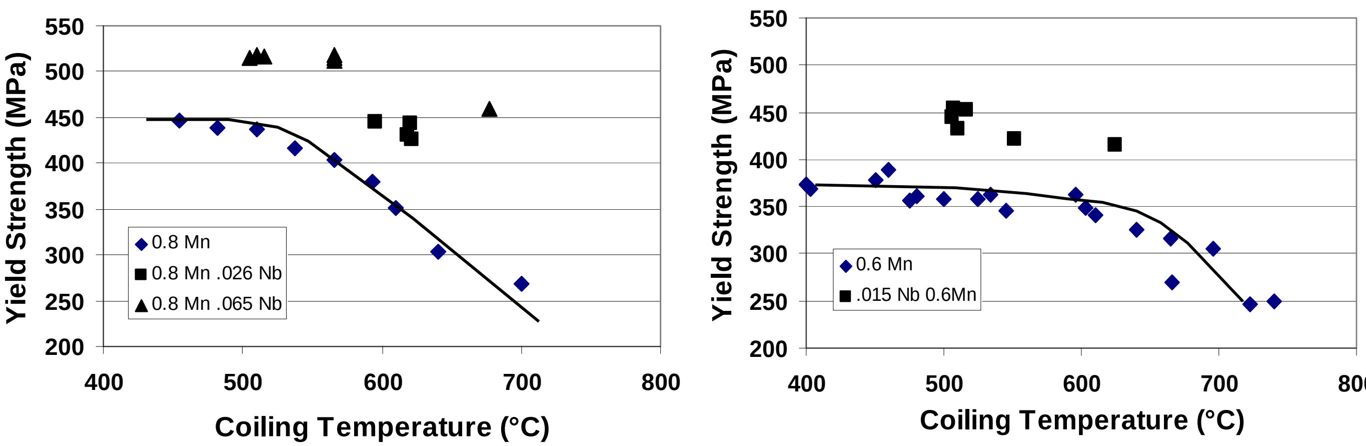
Microalloying
Recently, microalloyed steels with varying levels of niobium have been successfully produced via the CASTRIP process. Three Nb levels have been utilized; 0.014 wt%, 0.026 wt%, and 0.065wt%. Heat compositions are shown below in Table I.

Table I. Heat compositions for CASTRIP plant trials of Nb microalloyed steel.

C (wt%)	Mn (wt%)	Si (wt%)	Nb (wt%)
0.032	0.69	0.18	0.014
0.038	0.87	0.24	0.026
0.030	0.86	0.26	0.065

The goals of the niobium additions were to develop higher strength grades (Grades 410 to 550) and to extend the capability of Grade 380 down to thinner material. For each of the Nb heats, coiling temperatures and hot rolling reductions were varied in order to assess the effect of the Nb addition on the static recrystallization after hot rolling and the hardenability of steel, as well as to determine the precipitation hardening contribution of Nb. In the trial heats, the hot rolling mill exit temperature was held between 940 and 970°C (1725 and 1775°F).

Since only one heat of each composition was produced, limited data is available from the trials. However, production of these compositions has provided some valuable insights into the effects of the Nb on the properties of UCS steels. The yield strengths achieved for the two higher Nb heats are presented in Fig. 12 (a), and the yield strength results for the 0.014% Nb heat, produced with a lower Mn content, are presented in Fig. 12 (b). As a general summary, the Nb additions increased the yield strength at all coiling temperatures relative to the UCS base composition. The yield strength increased by about 70 to 100 MPa (10 to 15 ksi) for the 0.015% Nb and 0.026 Nb additions, and by about 140 to 175 MPa (20-25 ksi) for the 0.065 Nb addition. From Fig. 12 (a) it can be seen that the 0.026% Nb steel achieved significantly higher yield strengths than the 0.8 Mn base steel for similar coiling temperatures, and comparable yield strengths to when the 0.8 Mn base steel was coiled a low temperatures. Alternatively, the strengths achieved in the0.8Mn base steel at low coiling temperatures (~500°C) can be achieved at higher coiling temperatures (~600°C) with this Nb addition.

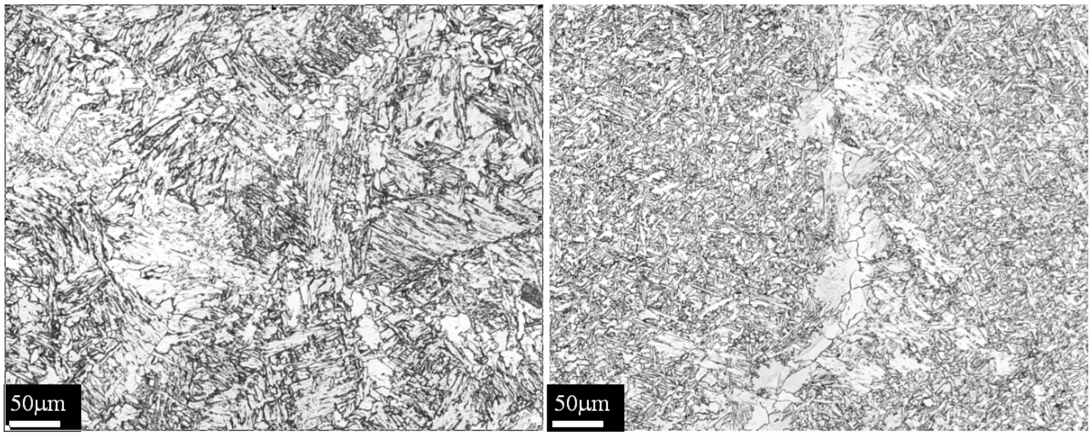


(a) (b)

Figure 12. Yield strength vs. coiling temperature (a) for 0.8 Mn grade and 0.8 Mn grades with Nb additions and (b) for 0.6 Mn grade and 0.6Mn grade with 0.015 Nb addition

TEM examination has only so far been conducted on the heat containing 0.026%Nb. In that case no evidence was found of precipitation despite coiling at 590-620°C (1100-1150°F), intending to induce precipitation of niobium. Metallographic examination did however reveal a predominately bainitic microstructure, as indicated in Fig. 13 (a). By comparison, the base steel coiled at substantially lower temperatures developed a microstructure comprising some grain boundary ferrite, shown in Figure 13 (b). Therefore the strengthening achieved with the 0.026% Nb steel would appear to be due primarily to microstructural hardening. This outcome can likely be attributed to Nb increasing the hardenability of the steel, which suppressed the formation of grain boundary ferrite and promoted the transformation to bainite. Isothermal ageing heat treatments of the hot rolled 0.026% Nb UCS material, comprising 20 minutes at 600 C and 650 C (1110 and 1200°F), induced precipitation of Nb(C,N), as confirmed by TEM examination.

This resulted in a further significant increase in yield strength of the material, as indicated in Fig. 14. Accordingly it would appear that the Nb was retained in solid solution during cooling and hot rolling, likely due to the transformation to bainite suppressing precipitation. Alternatively, a short ageing heat treatment that simulated the thermal cycle of strip through the annealing section of the galvanizing line at Nucor-Crawfordsville also induced a significant strength increase, approaching that achieved with the isothermal ageing at lower temperatures. This outcome provides the potential to utilize the galvanizing process to induce precipitation strengthening in high-strength, galvanized UCS products.



(a) (b)

Figure 13. Optical micrograph of (a) Nb microalloyed UCS Grade 380 and (b) standard UCS Grade 380. (200X, Nital etch)

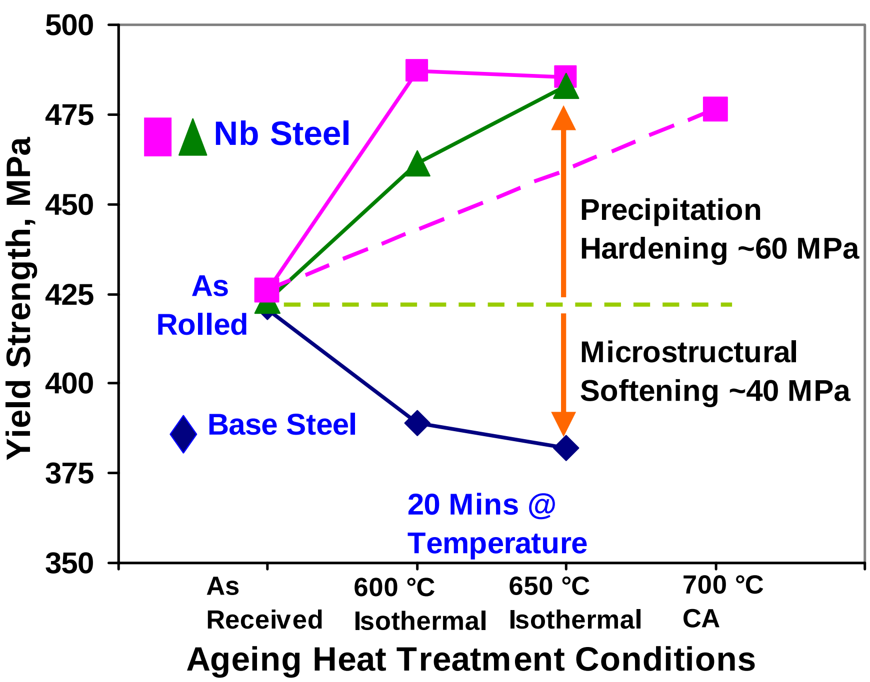


Figure 14. Response of UCS steels to Ageing compared to base steel.

The higher yield strengths achieved with the 0.065% Nb steel are possibly due to the higher Nb content inducing some precipitation of the Nb, though this phenomenon is yet to be confirmed by TEM examination. For the 0.014% Nb steel, the strength increase over the base composition also appeared to be predominately due to microstructural changes. Compared to the base steel produced with similar coiling temperatures and hot rolling reductions, the microstructure of the low Nb steel contained higher proportions of acicular ferrite, some bainite and less grain boundary ferrite. Again this outcome can probably be attributed to the increase in hardenability afforded by the small Nb addition.

The microalloyed steels also exhibited satisfactory ductility. As indicated in Fig. 15, the relationship between yield strength and total elongation is consistent with the results for the current Grade 380, produced using the 0.8 Mn chemistry.

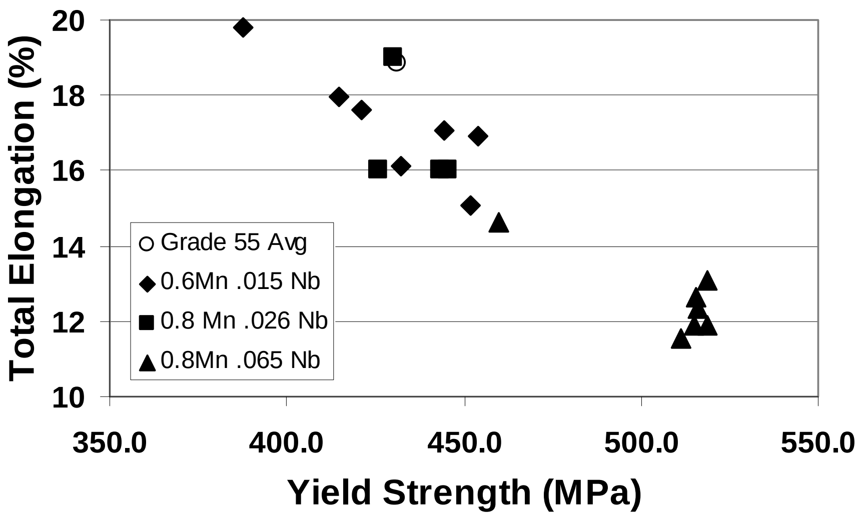


Figure. 15. Strength-elongation relationship for UCS Grade 380 and Nb trial heats.

Another significant attribute of the Nb microalloyed steels is that the apparent effect of hot reduction on the final yield strength has been considerably diminished. As shown previously, there is typically a decrease in strength with increasing hot reduction of plain C-Mn UCS steels. For each of the trial Nb heats, the coiling temperature was kept constant while the hot rolling reduction was varied. Although the data are limited, the trends in Fig.16 appear to indicate that the effect of hot reduction on yield strength is significantly reduced with the addition of Nb.

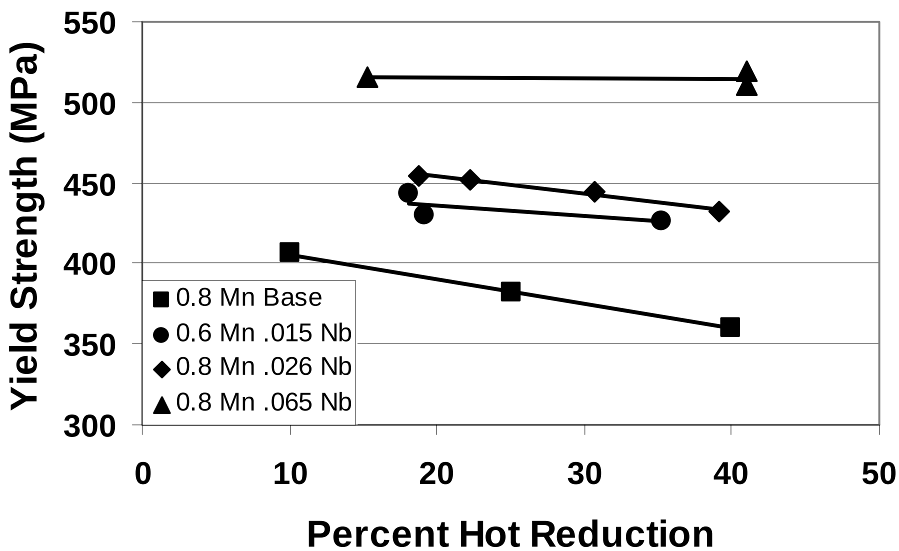


Figure 16. Effect of hot reduction on yield strength for the base 0.8 Mn composition and the Nb-bearing trial grades.

To investigate this effect further, the austenite grain size was measured at each thickness in the 0.026 Nb heat. Whereas the base chemistry tends to be fully recrystallized above about 25% hot reduction, the 0.026 Nb heat showed only limited recrystallization even at 40% reduction. This indicates that the solute Nb reduced the effect of hot reduction on the tensile properties by retarding the static recrystallization of austenite during hot rolling.

CONCLUSIONS

Recent trials and laboratory work have exhibited the potential to produce UCS steels with yield strengths from 380 MPa up to 550 MPa. By using higher levels of Mn, Grade 380 products are currently in regular production, albeit with limitations on gauge due to the effect of hot reduction on properties. Through temper rolling, the CASTRIP process appears capable of producing non-galvanized grades up to 480 MPa, while maintaining 10% minimum elongation. Further, cold reduction followed by recovering annealing during galvanizing provides light gauge (<0.9 mm) galvanized products up to 480 MPa and even 550 MPa, again while maintaining 10% elongation. Niobium bearing compositions showed even greater promise and versatility for UCS steels produced by the CASTRIP process. With strength levels exceeding 520 MPa directly off of the CASTRIP line and significantly reduced effects of hot reduction on tensile properties, Nb bearing UCS steels appear capable of producing hot band from 380 MPa up to 550 MPa over a wide range of gauges. Also, by precipitating the Nb during galvanizing, it also appears possible to produce galvanized products with the same and even higher strengths over the same gauge range. With these new grades, the CASTRIP product range has expanded beyond products readily available through conventional hot rolling mills with a new combination of high-strength, light-gauge UCS steels for a variety of structural applications.

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