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By

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DEVELOPMENT OF ULTRA-THIN CAST STRIP PRODUCTS BY THE CASTRIP® PROCESS

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ABSTRACT

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. The facility has been producing plain, low-carbon sheet steel since 2002. Some of the main parameters that influence the final microstructure and resultant mechanical properties of recently produced USC products are discussed. In particular, the role of particle-stimulated nucleation of intragranular acicular ferrite and the effects of inline hot rolling and accelerated cooling conditions on microstructural development and mechanical properties are presented. The performance of UCS products in the uniaxial tensile test and a range of formability tests is briefly described. Recent results for a Nb microalloyed steel are presented that highlight the potential for the development of thin, high strength strip products produced via strip casting technology.

1. 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 casting¹. 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 production for a range of applications.

In an integrated plant using conventional 200-250mm thick continuously cast slabs or the more recent compact strip mills utilising thin 50-100mm slabs, the production of low carbon thin strip of 1.5-2.0mm involves very high total reductions and multi-pass rolling schedules to refine the as-reheated/as-cast microstructure. The repeated recrystallisation of the austenite during multi-pass strip rolling leads to a fine austenite grain size, which in combination with accelerated cooling on the run-out table, produces a high ferrite nucleation density and a resultant fine ferrite grain size^{6,7}. Accordingly, one of the main strengthening mechanisms for conventional low carbon hot rolled strip products is ferrite grain size refinement. In comparison to the conventional processing route for thin strip, UCS production involves limited

rolling reduction to refine the as-cast microstructure. The final microstructure is thus dependent on the transformation products from relatively coarse austenite grains. The inclusion engineering practices feasible in producing thin strip by the CASTRIP process have been found to make it possible to induce the formation of a uniform dispersion of fine particles that, in combination with the coarse austenite grain size, assist in promoting particle-stimulated nucleation of intragranular acicular ferrite. An acicular ferrite microstructure is well recognised as being beneficial to strength and toughness due to the fine interlocking nature of the microstructure⁸.

The final microstructure of the recent UCS grades produced by the CASTRIP process consists of irregular shaped grain boundary ferrite, some Widmanstätten ferrite and fine intragranular acicular ferrite. This microstructure is considerably different from conventional hot rolled and cold rolled strip products. Accordingly the effects of the main processing variables such as the alloy design, hot rolling reduction and cooling conditions on the final microstructure and mechanical properties had to be established.

In addition an assessment of the formability of this microstructure was required. This paper provides an overview of recent experience with the manufacture of current UCS products produced by the CASTRIP process and presents some results from the assessment of these UCS products in a range of formability tests. Further, the potential to produce high strength thin strip

* CASTRIP is the registered trademark of Castrip LLC.

products for structural applications by utilising microalloying and recovery annealing are presented to, highlight some of the product development opportunities provided by strip casting technology

2. UCS MANUFACTURE

The CASTRIP process, similar to all twin-roll casting operations, utilises two counter rotating rolls to form two individual shells that are formed into a continuous sheet at the roll nip. The main components of the CASTRIP facilities at Nucor Steel Crawfordsville are depicted in Figure 1. The ladle size used is 110 metric tonnes, which feeds a large conventional tundish and then a smaller tundish or transition piece. The transition piece is designed to reduce the ferrostic 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 60-100m/min and the as cast strip thickness is typically 1.7mm or less. In order to limit scale growth on the strip surface a reducing 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, however typical reductions are less than 30%. 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.

The steel type used for the current grades in production is a low carbon (<0.05%)- manganese- silicon steel. This alloy design was adopted to ensure the deoxidation products of MnO and SiO₂ are liquid during the casting process to avoid clogging and to enhance the heat transfer rate⁹. 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 involved do not significantly elongate the inclusions, so that they are not necessarily harmful to formability and shearing.

Typical examples of the non-metallic inclusions present in UCS material now able to be produced by the CASTRIP process are given in Figure 2. The size range of the globular inclusions typically varied from about

10µm down to very fine particles (< 0.1µm), with a large proportion of the inclusions in the 0.5µm to 5µm size range. The composition of the inclusions was found to vary with the inclusion size, with the proportion of Mn decreasing and the proportion of Si increasing with decreasing inclusion size, which is consistent with the relative deoxidation potential of these elements. Some of the inclusions were composed of a complex mixture of phases including MnS, TiO and CuS. The size range and compositions of the inclusions in the UCS steels produced by the CASTRIP process can now be optimally engineered by virtue of careful control of the dissolved oxygen levels at the start of solidification and other alloying additions. The Mn-Si deoxidised steel practice provides flexibility for setting appropriate dissolved oxygen levels that are not possible in conventional Al killed steels and enables the non-equilibrium conditions generated by the very high solidification rates involved with strip casting to be fully exploited in generating the desired inclusion/ particle populations.

The non-metallic inclusion type and size distribution has been found to play a very beneficial role in the development of the final microstructure by promoting the intragranular nucleation of acicular ferrite (Section 3), without detriment to the formability of the strip (Section 4).

3. MICROSTRUCTURE DEVELOPMENT

An example of the austenite grain size in recently manufactured as-cast strip is shown in Figure 3a and the typical austenite grain morphology is schematically shown in Figure 3b. The morphology is typical of conventional castings with columnar grains extending from the surface that give way to an equiaxed zone in the centre. The austenite grain size is relatively coarse with individual grain widths and lengths greater than 200 and 450µm respectively. Subsurface grains are slightly finer than the grains in the central area of the strip, presumably reflecting the difference in thermal history and the influence of nucleation rate during initial solidification on the subsurface grain size⁵. Typical examples of the final microstructure of as-cast strip are shown in Figure 4a & b. Figure 4a shows the microstructure is composed of irregular shaped grain boundary ferrite that formed along the prior austenite grain boundaries, some Widmanstätten ferrite and intragranular acicular ferrite. Figure 4b shows acicular ferrite nucleating intragranularly on a large non-metallic inclusion. Such a microstructure is beneficial for improving the strength and toughness of steel, particularly in the case of a coarse austenite grain size.

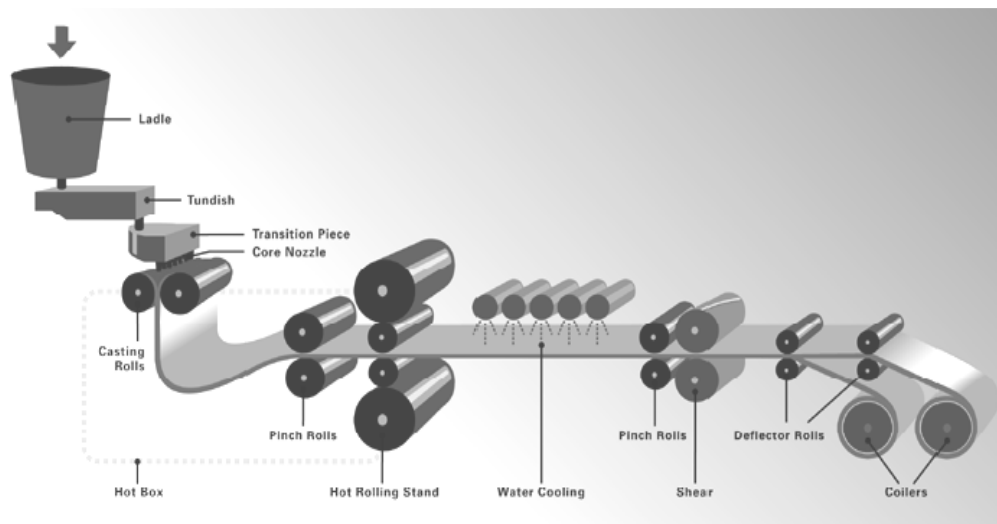


Figure 1. Main components of the CASTRIP process.

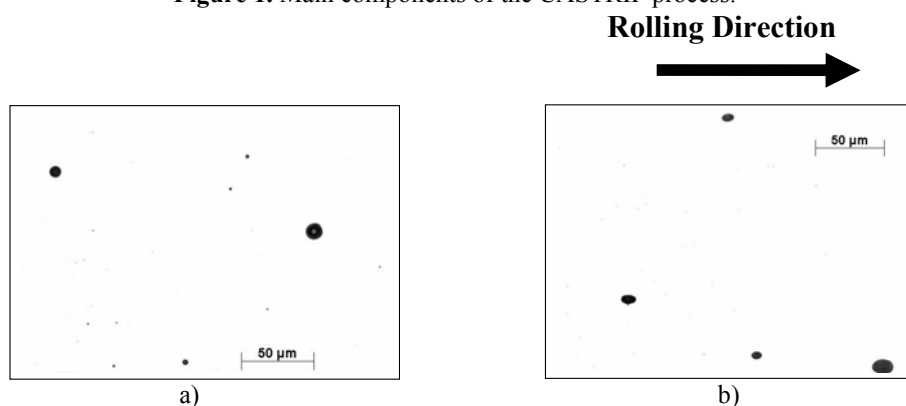


Figure 2. a) Typical worst case field showing globular inclusions found in as-cast UCS material, b) Elliptical inclusions found in hot rolled products.

The sequence leading to the formation of the acicular ferrite microstructure is shown schematically in Figure 5¹⁰. The first transformation product to form during the decomposition of austenite is a thin layer of allotriomorphic or grain boundary ferrite, which decorates the austenite boundaries. As the temperature decreases, Widmanstätten side plates can nucleate at the $\alpha - \gamma$ grain boundaries and grow into the untransformed region. Further cooling allows for the nucleation of acicular ferrite at inclusions. Subsequent nucleation events may stimulate other plates to nucleate sympathetically and therefore a one to one correlation with the number of nucleation events and inclusions is not expected¹¹. As many ferrite plates nucleate at essentially the same time, nearby plates impinge upon each other creating the characteristic fine interlocking plate morphology. The exact mechanism for the nucleation of acicular ferrite at inclusions is still under

debate,^{8,12,13} however it is considered that there are four mechanisms by which acicular ferrite can be nucleated on inclusions: a) the inclusion provides a heterogenous nucleation site which lowers the activation energy for nucleation, b) lattice matching between the crystal structures of ferrite and inclusion lowers the activation energy for nucleation,^{14,15} c) solute depletion (for example carbon, manganese) around the vicinity of the inclusion locally raises the ferrite transformation start temperature (A_{r3}) increasing the driving force for nucleation¹⁶ d) differences in thermal expansion between the inclusion and matrix locally raise the strain energy which reduces the activation energy for nucleation.

Inclusion size is critical to the intragranular nucleation of acicular ferrite. Larger particles increase the probability of nucleation of acicular ferrite and the minimum particle size required has been suggested to be 0.4-0.6 μm ^{17,18}. The

inclusion size distribution found in the UCS product recently produced by the CASTRIP process, fits well into this suggested particle size range. Besides the influence of the inclusion type, density and size on the formation of intragranular acicular ferrite, the other main factors are the austenite grain size, steel hardenability and the cooling rate through the transformation¹² Hence the alloy design, degree of inline hot rolling reduction and the cooling profile on the run-out table will be important process parameters and are discussed in the following sections.

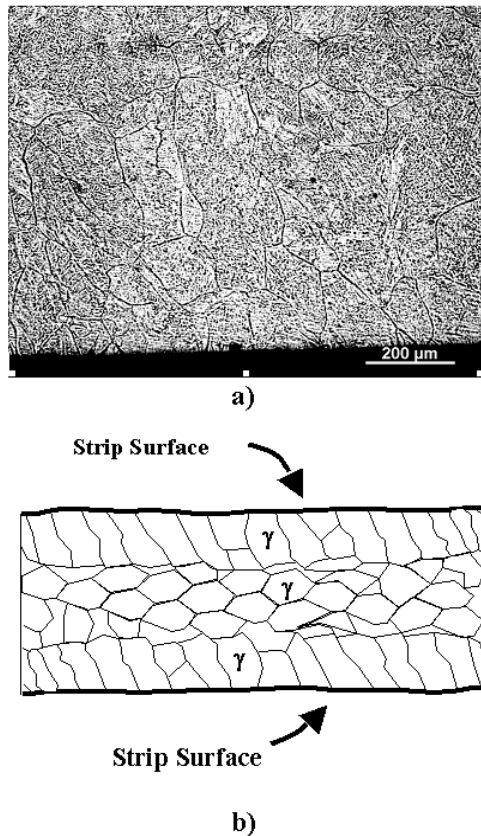


Figure 3. a) Photo micrograph through the cross section of a typical recently produced as-cast UCS product, etched in acidified picric acid, 100X (note the top of the photo is just above the mid thickness), b) schematic representation of the through thickness as-cast austenite grain structure,

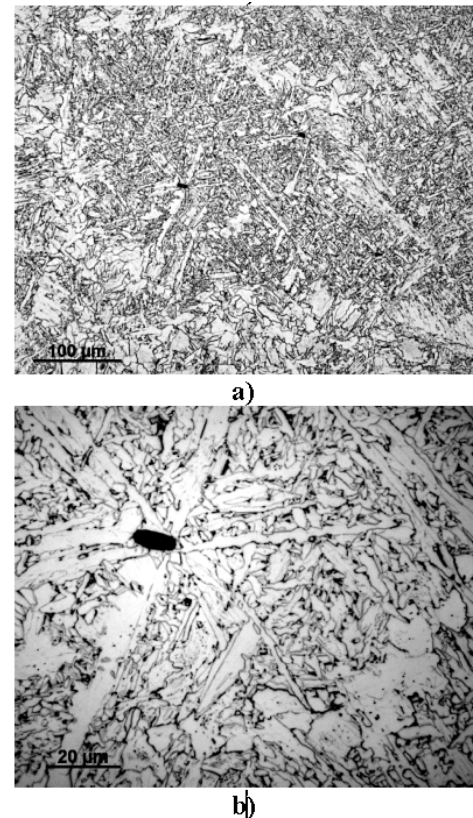


Figure 4. a) Transformed microstructure of as-cast UCS consisting predominantly of acicular ferrite with proeutectoid ferrite decorating the prior austenite grain boundaries, 200X, nital etch, d) acicular ferrite nucleating at a large non-metallic inclusion, 500X, nital etch.

3.1 Effect of Hot Reduction

The inline hot rolling mill is capable of hot rolling reductions up to 50%, however typical reductions are less than 30%. Figure 6 shows an example of the effect of hot rolling on the final austenite grain size measured through the thickness of a recent UCS strip. The as-cast austenite grain width varied from 120 μ m at the surface increasing to over 180 μ m at the strip centre. After a hot reduction of 13% the surface region recrystallised while the core region remained relatively unchanged. Static recrystallisation of the austenite grains resulted in a dramatic decrease in the grain size at the surface to approximately 50 μ m. Increasing the amount of strain extended the recrystallisation process further towards the strip centre. The average grain size of the strip surface layer was only marginally reduced by the increase in deformation. After 29% hot reduction, recrystallisation had extended through the full strip thickness, though a few isolated large un-recrystallised grains remained in the strip centre. The subsurface grains recrystallising before the central region is attributable to the finer as-cast austenite

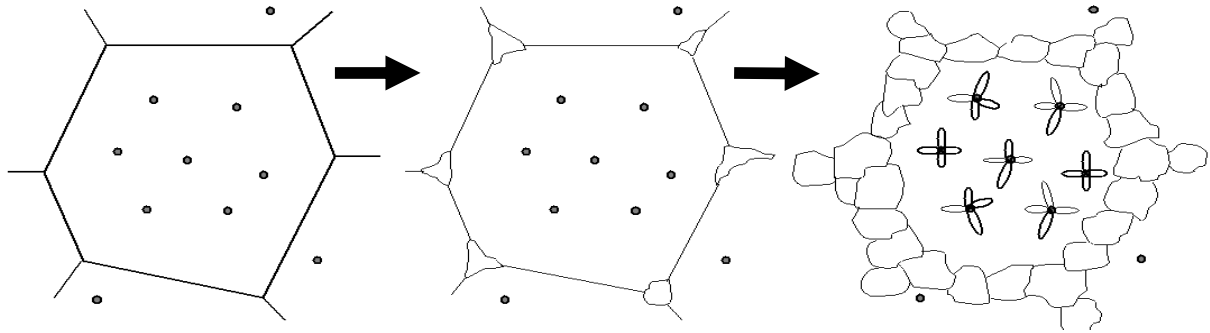


Figure 5. Schematic of the formation of acicular ferrite microstructures. After Barbaro 2006¹⁰

grains in the subsurface area and the through-thickness strain gradient induced by friction between the strip surface and the work rolls.

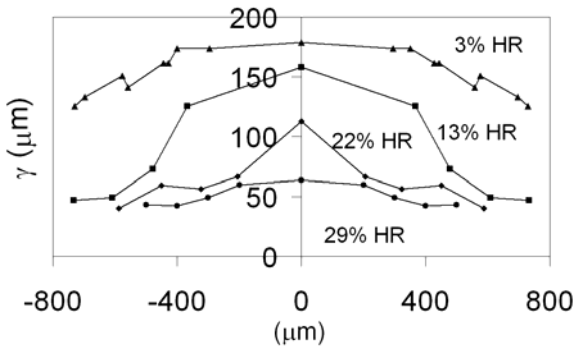


Figure 6. Effect of hot rolling on the evolution of austenite grain size measured through the thickness of a UCS strip.

The reduction in the austenite grain size from hot rolling was clearly reflected in the final transformed microstructure of the recently produced USC product. Figures 7a - f show the evolution of the final microstructure with increasing hot rolling reduction for a constant coiling temperature. It can be seen that the proportion of acicular ferrite decreases and the proportion of grain boundary ferrite/polygonal ferrite increases with increasing hot rolling reduction. The ferrite grain size was also refined with increasing reduction. These observations are presented quantitatively in Figures 6a & 6b. As previously described, the as-cast condition was composed predominantly of acicular ferrite with grain boundary ferrite decorating the prior austenite grain boundaries. The near surface region, where the austenite grain size was the finest, was composed of a higher proportion of irregular shaped grain boundary ferrite. At deformations up to about 10% no significant change in the proportion of acicular ferrite was observed. Between 15 – 25% hot reduction the amount of acicular ferrite decreased significantly, as austenite recrystallisation occurred

increasingly towards the strip centre. The pro-eutectoid ferrite grain size also decreased with increasing hot reduction reflecting the higher grain boundary area of the refined austenite grain size providing many more ferrite nucleation sites. Increasing the hot deformations above 25% decreased the proportion of acicular ferrite and the ferrite grain size further, albeit to a lesser extent. Decreasing the carbon equivalent by a reduction of the carbon content resulted in a reduction in the amount of acicular ferrite, consistent with the reduction in the hardenability of the steel.

These changes in microstructure are reflected by a change in the form of the engineering stress-strain curve and mechanical properties of the steel, shown in Figure 8a. Figure 8b shows schematically the changes in the tensile properties with inline hot rolling reduction, for a constant coiling temperature. The reduction in the proportion of acicular ferrite results in a reduction in strength, increase in total elongation and return of the yield point for reduction levels up to about 20%, while at the higher hot rolling reductions the increasing refinement of the ferrite leads to a slight increase in strength, higher total elongation and an increase in the yield point elongation. The effect of hot reduction on the microstructure and final properties is however, also a function of coiling temperature and the steel composition, such that the effect of hot rolling reduction is less at high coiling temperatures (low cooling rates) than at low coiling temperatures.

3.2 Effect of Coiling Temperature

The effect of the coiling temperature on the strength of two recently produced UCS steels with different manganese levels is shown in Figure 9. The yield strength increased steadily with decreasing coiling temperature for temperatures down to about 550 °C, whereafter the strength only slightly increased with further reductions in coiling temperature. The higher manganese level provided an increase in strength, particularly at the lower coiling temperatures. The effect of lowering the coiling

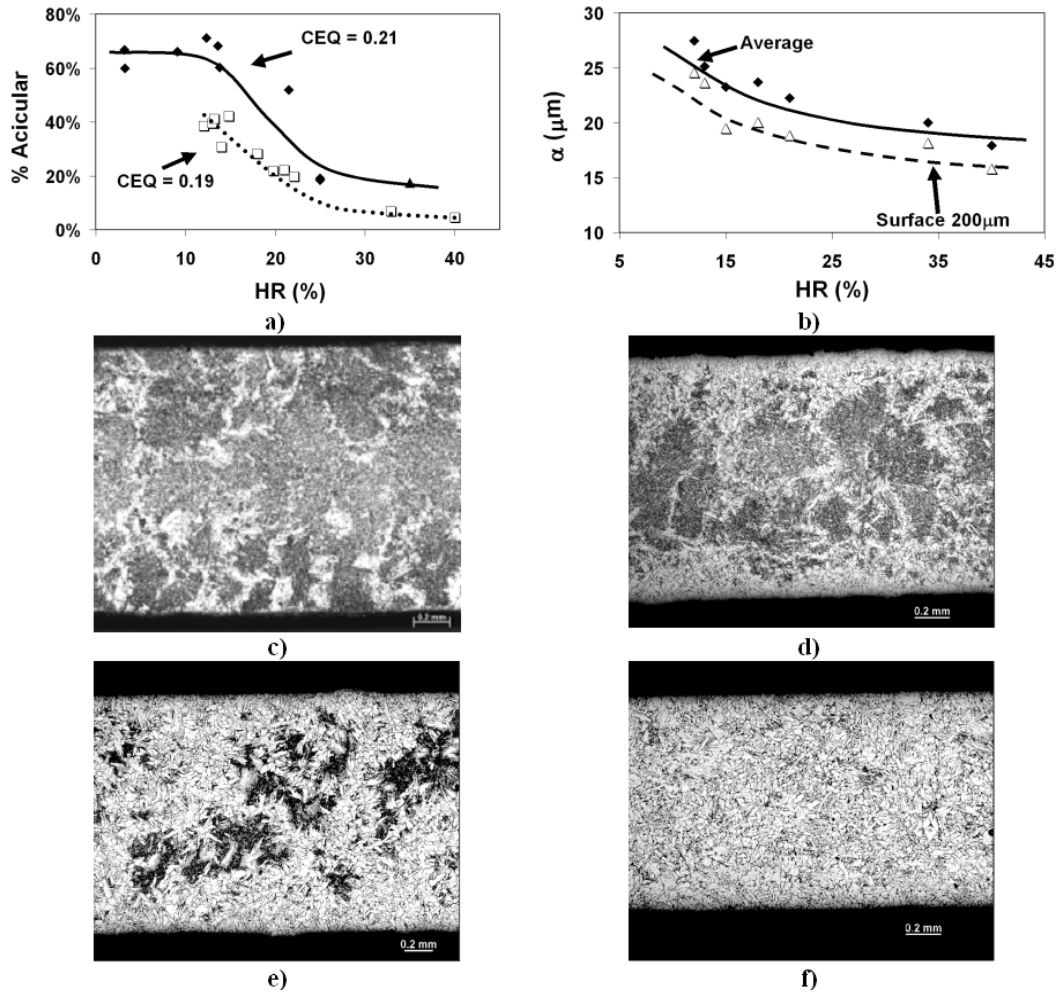


Figure 7. Effect of hot rolling on the evolution of microstructure of ultra thin cast strip recently produced by the CASTRIP process a) acicular ferrite content b) allotriomorphic / irregular grain boundary ferrite grain size, c) as-cast microstructure d) 13% hot reduction e) 22% hot reduction f) 29% hot reduction. 25X, nital etch.

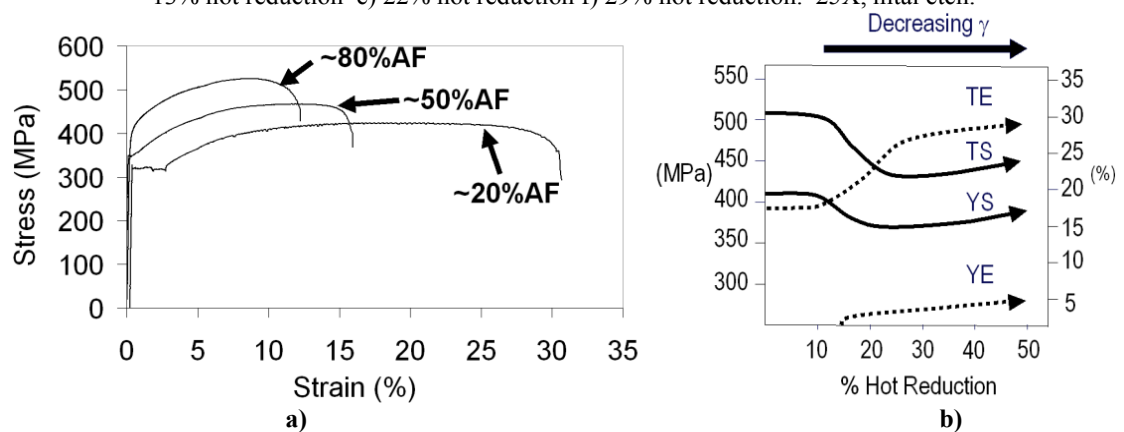


Figure 8. Effect of hot rolling reduction on the mechanical properties of UCS material. a) engineering stress strain curves for as-cast, 14% and 25% hot reduction. b) schematic representation of the mechanical properties of UCS material as a function of hot rolling reduction at constant coiling temperature. Total Elongation (TE), Tensile Stress (TS), Yield Stress (YS) and Yield Elongation (YE).

temperature was to limit the formation of grain boundary ferrite and accordingly increased the proportion of acicular ferrite, providing the increase in strength recorded. The higher manganese content assisted in further increasing the proportion of acicular ferrite through increasing the steel's hardenability. For coiling temperatures below about 550 °C, the microstructure was comprised mostly of acicular ferrite with a small proportion of grain boundary ferrite. As the cooling rate was not sufficient to suppress the formation of grain boundary ferrite, the strength approached a plateau for coiling temperatures below 550°C. Overall the combination of coiling temperature control and modest alloy adjustments enables the potential for a range of structural grades to be produced from a low C-Mn-Si steel.

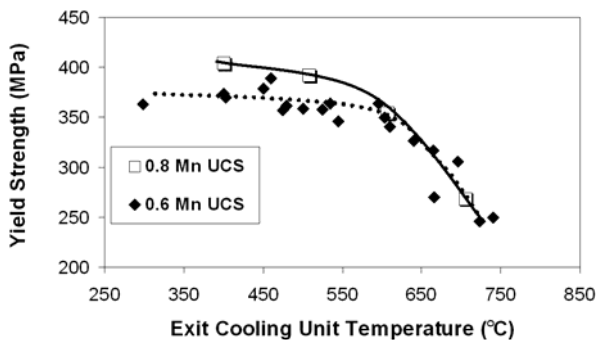


Figure 9. Effect of run out table cooling conditions on the yield strength of UCS.

4. MECHANICAL PROPERTIES

The mechanical properties of the current UCS grades in present production were assessed via uniaxial tensile tests and a range of standard formability tests to gain an

appreciation of the behaviour of these products to forming and fabrication processes. To provide comparative data, several commercial, structural quality, hot rolled and cold rolled and continuously annealed strip products of similar strengths and thicknesses to the UCS products were concurrently tested. These comparative steels are in regular production at BlueScope Steel and the typical compositions and tensile properties of the samples used for the testing are given in Table 1.

4.1 Tensile Properties

The main commercial and structural strip grades currently produced at the Crawfordsville CASTRIP facility are ASTM A1011M Grade CS and SS Grades 275, 340 and 380. These grades are achieved via adjustments to the coiling temperature and the manganese content. The typical chemical compositions and tensile properties for each structural grade are given in Table 1. The strength requirements for these grades were comfortably achieved. Of particular note from the tensile properties is the relatively high tensile strength and low yield/tensile strength ratio. A low yield/tensile strength ratio does afford the steel considerable strain hardening capacity, which can aid in roll forming processes. This behaviour can be attributed to the microstructure being mainly a mixture of soft irregular ferrite/grain boundary ferrite and harder acicular ferrite. The presence of acicular ferrite does however result in the total elongation values being somewhat lower than recorded with conventional hot and cold rolled strip grades of similar strength. This outcome can be attributed to the higher dislocation density of the acicular ferrite compared to polygonal ferrite. While the total elongation from uniaxial tensile test is used as a broad measure of ductility, it does not necessarily reflect the various formability characteristics of the steel.

Table 1. Comparison of UCS products with conventional hot rolled (HR) and cold rolled and annealed (CR & CA) products.

Grade	C (wt%)	Si (wt%)	Mn (wt%)	Al (wt%)	N (ppm)	t (mm)	YS (MPa)	TS (MPa)	TE (%)
275 UCS	0.03 – 0.05	0.22-0.30	0.6 – 0.9	<0.003	35-90	1.0 – 1.7	325	430	28
340 UCS	0.03 – 0.05	0.22-0.30	0.6 – 0.9	<0.003	35-90	1.0 – 1.7	375	475	21
380 UCS	0.03 – 0.05	0.22-0.30	0.6 – 0.9	<0.003	35-90	1.2 – 1.7	440	530	18
200 HR	0.06	0.005	0.25	0.035	34	1.5	297	380	34
300 HR	0.15	0.010	0.78	0.034	34	1.5	370	490	28
360 HR	0.15	0.010	0.78	0.042	46	1.5	415	510	22
300 CR & CA	0.06	0.005	0.22	0.042	32	1.0 – 1.2	340	400	30
300 CR & CA	0.15	0.005	0.75	0.035	30	1.5	380	489	29
350 CR & CA	0.14	0.005	1.00	0.035	33	1.5	369	468	34

Total elongation reflects the aggregation of the elongations arising from the various segments of the uniaxial tensile test; such as the yield point elongation, uniform elongation and the post uniform elongation or necking strain. Typical uniaxial stress-strain curves for each of the three main UCS grades, described above, were analysed to determine the elongations for the various segments of the uniaxial tensile test. The results are presented in Figure 10a & b, and are compared with the results for the structural quality light gauge hot and cold rolled strip grades described in Table 1. The total elongation values for the UCS products were lower than similar strength hot or cold rolled grades, with the difference increasing for the higher strength grades. This behaviour reflects the increasing volume fraction of acicular ferrite in the microstructure with increasing strength. A contributing factor for part of the difference in total elongation is the lower post uniform elongation exhibited by the UCS products. In the case of the UCS SS Grade 275 material, the lower post elongation accounts for the majority of the difference in total elongation with the similar strength cold rolled and annealed grade and half the difference with the low strength hot rolled grade. This behaviour probably reflects the strain localisation to the grain boundary ferrite phase due to the higher dislocation density, higher strength of the acicular ferrite phase. The lower volume fraction of grain boundary/polygonal ferrite in the UCS product compared with the low carbon, polygonal ferrite-pearlite, conventional hot/cold rolled products, would then lead to more rapid fracture and lower post uniform elongation. The post uniform elongation is however, of limited practical significance as the material has already begun to locally thin. Another contributing factor to the lower total elongation values for the UCS products, particularly for A1011M SS Grades 340 and 380, is the minimal yield point elongation due to the high volume fraction of acicular ferrite.

One of the most significant indicators of formability from the uniaxial tensile test is the Holloman strain hardening exponent, (n value). From Figure 10b it can be seen that for UCS SS Grade 275, the n value was in the order of 0.19, which is satisfactory for a structural quality grade and similar to that exhibited by the cold rolled and continuously annealed 0.06wt%C 300 CR & CA strip steel. For the higher strength UCS grades the n value decreased, as would be expected, with increasing strength however, for Grade 340, the n value was only slightly less than a comparable strength cold rolled and continuously annealed 0.15wt%C 300 CR & CA high strength grade, while the UCS380 still exhibited a n value of about 0.12. As the n value is only one measure of formability, the results from other formability assessment tests are discussed in the following sections.

4.2 Stretch Flange-ability

The forming of components from USC strip can require the stretching of the sheared or punched edge of the strip. The stretch flange-ability of a steel is thus of considerable importance. The hole expansion test is utilised to assess the stretch flange-ability of steel strip products. The test is carried out by first punching a hole in a steel blank which is then expanded by a conical punch until a through thickness crack is observed. The hole expansion property, λ Eq.1, is taken as the change in hole diameter divided by the original hole diameter.

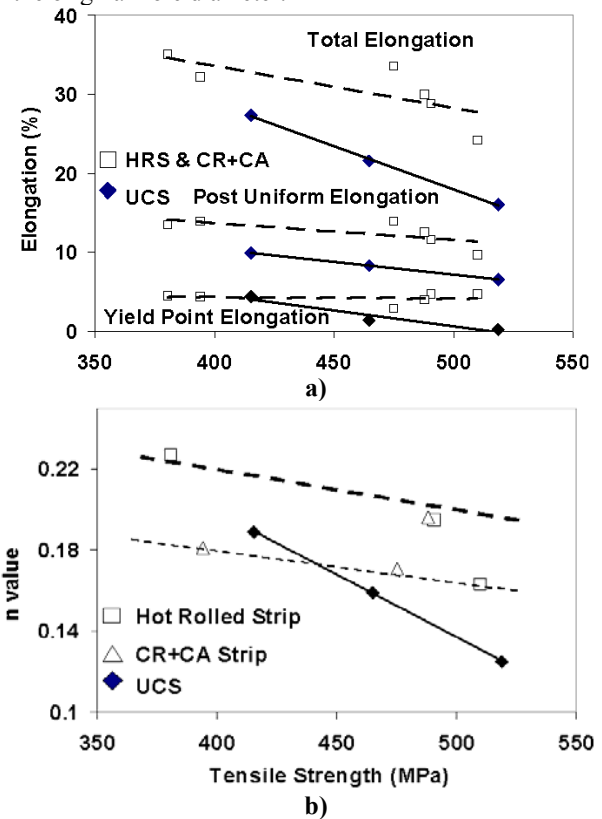


Figure 10. a) Comparison of elongation components from the uniaxial tensile test for UCS, HRS and CR & CA strip products, b) comparison of the strain hardening capabilities for UCS, HRS and CR & CA products. Gauge length 80mm.

$$\lambda = \frac{d_f - d_0}{d_0} \times 100\% \quad (1)$$

Where d_0 and d_f are the initial and final diameter of the punched hole. Many factors have been implicated in determining the hole expansion property of steel. Correlations linked to the mechanical properties derived from the uniaxial tensile test have indicated that high

levels of ductility and plastic anisotropy, high YS/TS ratios and low yield and tensile strengths all improve the hole expansion property.^{19,20,21,22,23} With respect to microstructural features, a high degree of microstructural homogeneity improves the hole expansion performance. Strong correlations have been produced with the ratio of the hardness of the matrix compared to the secondary phase²⁴. The greater the difference in hardness, the lower the hole expansion property. Accordingly microstructures containing large proportions of pearlite and martensite, as well as strongly defined microstructural banding, are particularly deleterious to the hole expansion property. In contrast microstructures with high proportions of bainite have been found to have a superior hole expansion property²⁵. The hole expansion performance has also been found to be degraded by the presence of elongated MnS inclusions²⁶.

conventional hot rolled and cold rolled structural grades the hole expansion property decreased with increasing tensile strength and decreasing total elongation. The UCS products however did not follow this trend, maintaining a high hole expansion performance at high strength levels and low total elongations. Possible reasons for the better performance of the UCS products could be the absence of elongated MnS inclusions and alumina clusters or the high degree of homogeneity of the acicular ferrite microstructure. To assess the significance of an acicular ferrite microstructure, a sample of UCS Grade 275 was given a normalising heat treatment, resulting in a conventional fine-grained polygonal ferrite and pearlite microstructure. The hole expansion results are included in Figures 10a and 10b. The hole expansion performance was lower in the normalised condition, suggesting the high hole expansion performance of the UCS products was mainly due to the acicular ferrite microstructure. Acicular ferrite consisting of small ferrite plates with a fine distribution of small carbides provides a high degree of homogeneity that improves micro plasticity and provides the improved hole expansion performance.

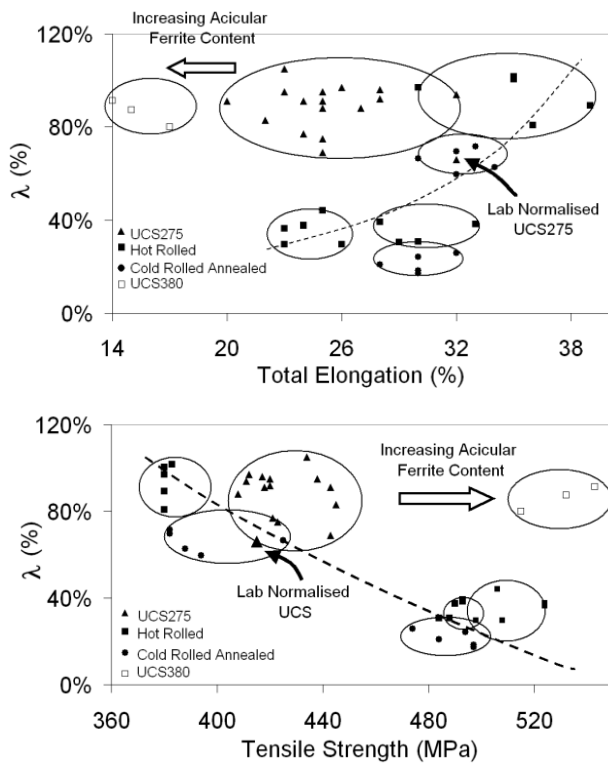


Figure 11. Stretch Flange-ability as measured by the hole expansion test of UCS Grade 275 and Grade 380 compared to equivalent conventional structural quality hot rolled and cold rolled strip a) λ as a function of TS b) λ as a function of TE.

Figure 11 shows the hole expansion results for UCS SS Grades 275 and 380 as a function of the tensile strength (Fig.11a) and total elongation (Fig. 11b) compared to equivalent conventional light gauge hot rolled and cold rolled, continuously annealed products. For the

4.3 Biaxial Stretch

Biaxial tension is one of the most common modes of plastic deformation found in cold forming such as drawing and stretching operations. Erichsen dome tests are a convenient way to assess the biaxial formability of sheet metals. In this test a spherical indenter is pressed into a test piece until a through thickness crack is observed. The height (Erichsen Cup Height, or ECH) of the indent is an indication of the ability of the material to withstand biaxial forming operations. Failure in these operations usually occurs by localised necking and or by cracking around pre-existing defects or second phase particles in the microstructure²⁷.

The Erichsen dome test results for the UCS grades 275, 340 and 380 and the conventionally manufactured low carbon, aluminium killed hot rolled and cold rolled, continuously annealed strip products (Table 1) are given in Figure 12. The performance of these UCS products was found to be comparable to the hot rolled and cold rolled and continuously annealed strip grades at similar strip thicknesses and perhaps slightly better than the 360 MPa high strength hot rolled grade.

4.4 Normal Anisotropy

During forming, sheet metal is subjected to complex strain histories, such that material characteristics that describe stretchability, like yield behaviour and n value (strain hardening exponent), may not adequately describe forming performance. The resistance of material to thinning, normal anisotropy, or r-value, more adequately

describes a materials performance during drawing. Materials are often characterised by the average normal anisotropy, r_m , and the planar anisotropy, Δr . These are related to r by the following equations.

$$r_m = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (2)$$

$$\Delta r = \frac{r_0 + r_{90} - 2r_{45}}{2} \quad (3)$$

Where r_0 , r_{45} and r_{90} are r values determined in the rolling direction, at 45° to the rolling direction and transverse to the rolling direction of sheet or strip, respectively. Drawability improves with increasing r_m ,

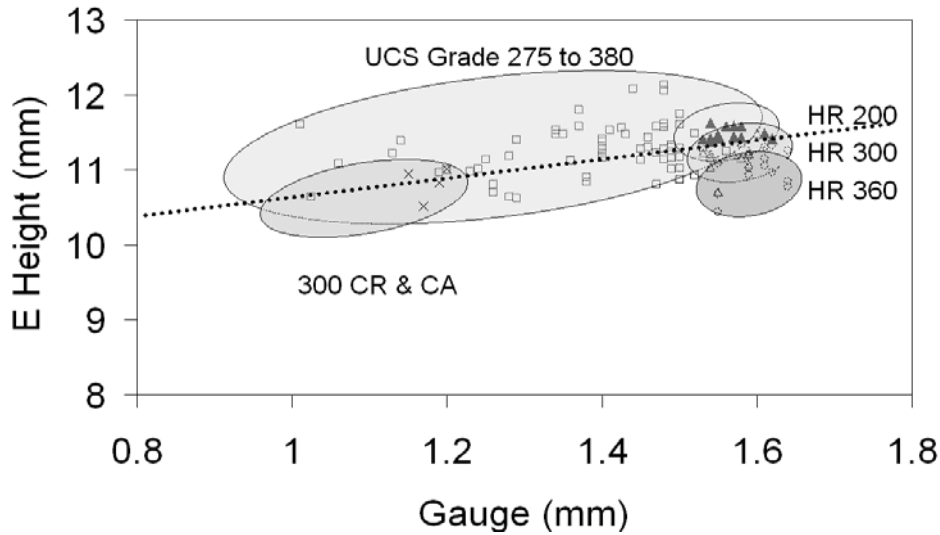


Figure 12. Strip thickness versus Erichsen dome height for recent UCS products compared to conventional hot rolled and cold rolled annealed products.

Table 2. Typical r_m and Δr values for UCS compared with similar thickness and strength hot and cold rolled strip.

Material	r_m	Δr
UCS (grades 275 to 380)	1.03	0.04
200 HR	0.96	0.10
300 HR	0.93	0.02
300 CR	1.03	0.41

and by minimizing Δr (earring)²⁸. Typically, low carbon hot rolled steel strip has r_m values of 0.8 to 1.0. The UCS products, produced with typical levels of hot reduction (up to 30%), are almost isotropic in nature, with r_m values of approximately 1.0 and with low planar anisotropy (low ΔR) of 0.04. Table 2 summaries the r_m and Δr of these UCS products and comparative (similar thickness and strength) hot and cold rolled strip products.

The variation of r_m with the degree of hot reduction is shown in Figure 13. Although the results at high

reductions are as yet limited, it would appear that the normal anisotropy was only slightly reduced with increasing hot reduction up to about 35%.

The superior normal anisotropy of UCS products up to 15% is thought to be due to the large almost through half thickness columnar austenite grains. This has been shown²⁹ to result in a large volume fraction with the γ -fibre orientation and this tends to decrease as the grain size decreases with increasing reduction, or post casting processing. Cramb³⁰ has also observed that hot

reduction causes a slight increase of {111} intensity and decrease of {100} intensity as compared to the as-cast strip.

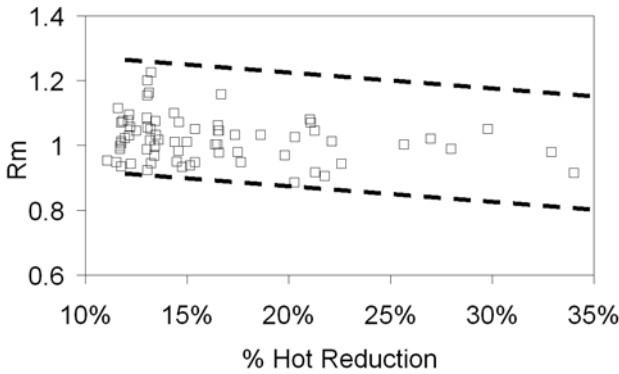


Figure 13. Variation of normal planar anisotropy (r_m) with hot reduction.

The drawability of UCS material was further assessed by determining the limiting draw ratio (LDR) using Swift cups, with a cup diameter of 50mm. The LDR is the maximum drawable blank diameter, D/d (diameter of blank/ diameter of punch). A UCS Grade 275, 1.4 mm, product was found to have an LDR of approximately 2.3 (minimum blank diameter of 115mm), which is consistent with the r_m of 1.03³¹. The result also compared favourably with a conventional 300 MPa hot band, which gave a LDR of 2.1, probably reflecting the slightly higher r_m of this UCS material.

4.5 Forming Limit Diagram

The forming limit diagram determined for each grade are given in Figures 14a & b, the latter also includes the results for a high strength cold rolled and continuously annealed forming grade. The estimated FLD_0 strain based upon the strain hardening exponent (n value) and strip thickness is also given in Table 3. The shape of the forming limit diagrams was comparable to that of conventional strip products and the measured FLD_0 strains were in close agreement with the estimated FLD_0 strains. The latter result is consistent with the behaviour of conventional hot and cold rolled strip grades, whereby the FLD_0 strain is a function of the 'n value' and strip thickness³². Moreover the results for the UCS Grade 50 were similar to a comparable strength cold rolled and continuously annealed high strength grade.

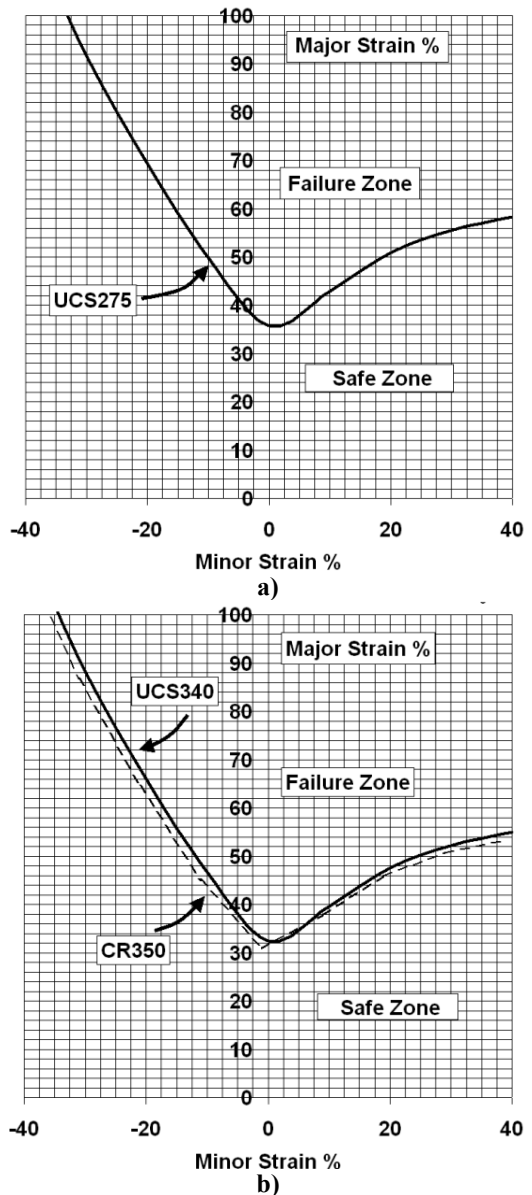


Figure 14. Forming limit diagrams for grades a) UCS Grade 275, b) UCS Grade 340 & CR & CA 350.

5. HIGHER STRENGTH GRADE DEVELOPMENT

While the initial focus has been on developing a range of grades up to ASTM A1011M SS Grade 380, more recent development effort has been directed at capitalising on the ability of the CASTRIP process to readily produce thin high strength strip, to develop products with yield strengths over 500 MPa (72ksi). Two approaches have been adopted: the use of microalloying additions to achieve higher strength grades within the thickness range directly available from the process, and cold rolling and recovery annealing to extend the thickness range for high

strength grades to lighter sections. The initial results from these investigations are briefly described below.

5.1 Microalloyed Steel Development

A niobium microalloyed steel was successfully strip cast recently by the CASTRIP process with the view to producing a high strength strip product for structural applications. A 0.026% Nb addition was made to a 0.04 C, 0.85 Mn, 0.25 Si steel. The strip was cast at 1.7mm thick and inline hot rolled to a range of strip thickness from 1.5mm to 1.1mm. The strip was coiled at 590-620 °C to facilitate precipitation hardening by Nb. The strength levels achieved are presented in Figure 15 in comparison to the strength levels achievable from the base composition over a range of coiling temperatures. It can be seen that the Nb bearing steel achieved yield strengths in the range of 420-440 MPa and tensile strengths were about 510 MPa. Compared to the C-Mn-Si base steel processed with the same coiling temperature as the Nb microalloyed steel, the Nb bearing steel produced substantially higher strength levels. The base steel had to be coiled at very low temperatures to achieve comparable strength levels to the Nb microalloyed steel. Moreover, the strength levels for the Nb steel were not significantly affected by the degree of inline hot reduction (19-37%). The ductility of the Nb microalloyed steel was similar to the base steel of equivalent strength, with total elongations of about 15%, a n value of about 0.11, a r_m of nearly 1.0, a Δr of 0.04, and a hole expansion ratio of about 90%, Table 4.

The higher strength of the Nb bearing steel appeared to be due mostly to microstructural hardening. The microstructure of the Nb steel was predominantly bainite for all strip thicknesses. In contrast the base steel with similar strength by coiling at a low coiling temperature, had the usual microstructure comprising mostly acicular ferrite with some grain boundary ferrite (Figure 16). TEM examination did not reveal any Nb precipitation, indicating the Nb had been retained in solution and that the strengthening produced was mainly due to microstructural effects, presumably a function of the higher hardenability provided by Nb in solution

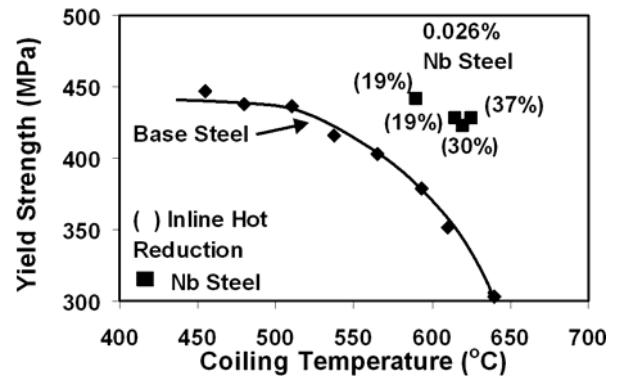
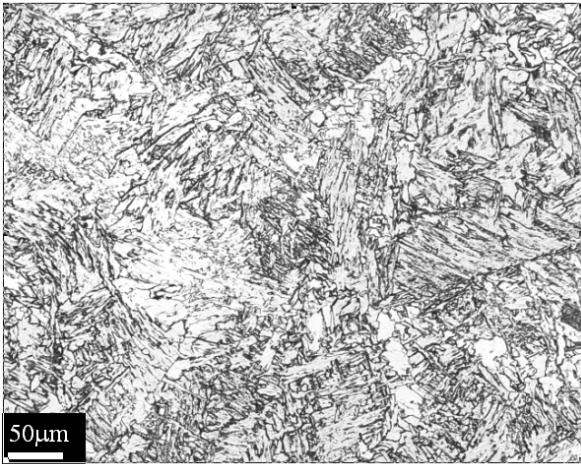


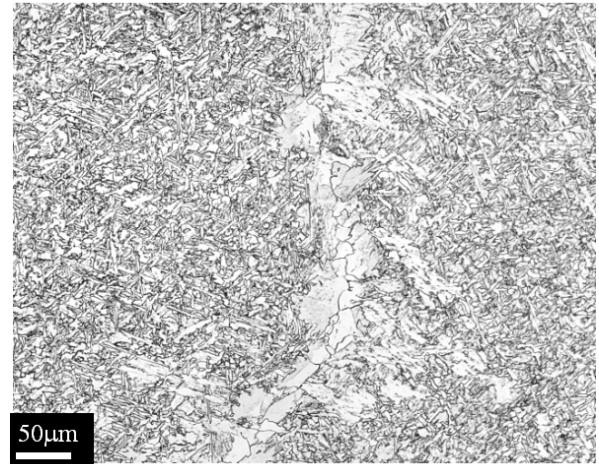
Figure 15. Effect of coiling temperature on strip yield strength with and without additions of 0.026%Nb.

Consequently ageing heat treatments were carried out at 600°C and 650°C for 20 minutes, which produced a significant increase in strength, with yield strengths of about 480MPa (~70 ksi) realised (Figure 17a). Comparing the response to the ageing heat treatments of the Nb microalloyed steel and the base steel, the strengthening increment due to Nb precipitation was about 110 MPa. In addition short time ageing heat treatments were carried out to simulate the ageing potential from processing the Nb microalloyed steel through a galvanising line. The results are given in Figure 17b, and clearly show that for a peak annealing temperature of 700°C, significant strengthening was realised, with strength levels approaching that achieved for the longer times at lower temperatures. The potential exists therefore to produce a thin, high strength, strip product for structural applications through the use of Nb microalloying. A slightly higher Nb level should realise yield strengths well in excess of 500MPa.

In view of the consistent strength of the Nb steel over the range of hot reductions applied during the trial (19-37%), the prior austenite grain size was determined for each strip thickness. The austenite grain size measurements indicated that only very limited recrystallisation had occurred at high hot rolling reductions, whereas in the case of the base steel, discussed previously, it is almost fully recrystallised at reductions over about 25%. The hot rolling temperature was approximately 950 °C. The relatively coarse austenite grain size of the Nb UCS steel for all strip thicknesses would account for the consistent strength levels recorded. Accordingly, it would seem that the retardation of austenite recrystallisation could be attributed to the presence of solute Nb.



a)



b)

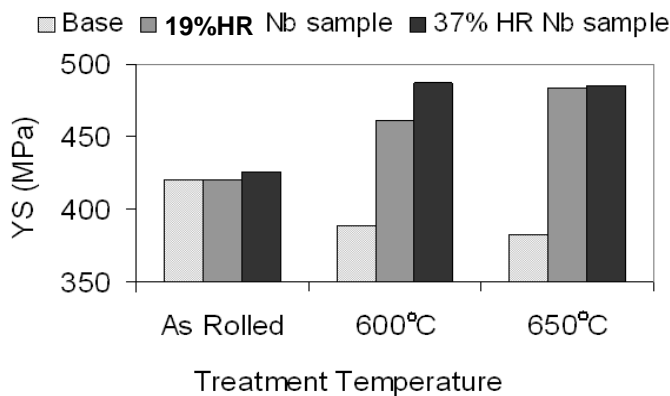
Figure 16. Optical micrograph of a) Nb microalloyed UCS SS Grade 380 and b) standard UCS SS Grade 380. 200X, Nital Etch.

Table 3. Tensile properties of the steels used in the forming limit diagrams. Gauge length 80mm.

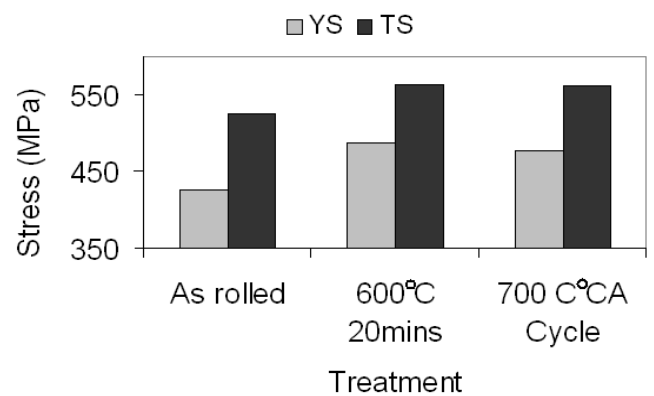
Grade	t (mm)	YS (MPa)	TS (MPa)	TE (%)	n value	FLD Predicted	FLD Actual
UCS275	1.2mm	297	412	30	0.19	30.2%	32.0%
UCS340	1.1mm	362	466	22	0.16	33.8%	35.8%
CR350	1.0mm	369	468	34	0.17	31.9%	31.0%

Table 4. Mechanical property results for the Nb microalloyed UCS steel. (80mm gauge length).

Coil	HR (%)	t (mm)	YS (MPa)	TS (MPa)	TE (%)	n value	r _m	Δr	HE, %
3	19	1.5	430	512	15	0.11	0.97	0.02	92
5	37	1.1	427	512	15	0.12	0.96	0.06	88



a)



b)

Figure 17. a) Effect of a 20min post coiling heat treatment on the yield strength of Nb micro-alloyed UCS, b) Effect of post coiling simulated galvanising line annealing cycle on yield and tensile strength of Nb micro-alloyed UCS.

5.2 Recovery Annealed Grade

The capability of readily producing thin high strength strip products via the CASTRIP process, provides the potential to develop an even thinner (< 0.9mm), higher strength galvanised structural grade (>500 MPa, 72 ksi) by utilising cold rolling and recovery annealing. While ASTM A1011M requires a minimum of 7% and 6% total elongation for SS Grades 500 and 550 respectively, the building code requirements for structural cold-formed sections, stipulate that steel strip grades exhibit a minimum ductility of 10% total elongation for joint integrity. Such a requirement can be difficult to achieve with conventional high strength recovery annealed strip due to the high degree of cold reduction required when using 2.0-2.5mm hot rolled strip as the feedstock. Utilising thin, high strength UCS products enables lower levels of cold reduction to be used to achieve the final thickness required, which should assist in providing improved ductility after recovery annealing.

Following a preliminary laboratory study, full-scale mill trials were undertaken using UCS SS Grade 340 as the feedstock, which was cold rolled to 0.75mm using a range of cold rolling reductions. The strength and ductility levels achieved after recovery annealing and galvanising are shown in Figure 18 as a function of the level of cold rolling reduction. The results show that for cold reductions below about 30%, total elongations in excess of 10% were achieved in combination with yield strengths in the range of 550-600 MPa. The material also passed a 0T bend test. These results indicate the potential to achieve high strength products down to quite thin gauges that meet the ductility requirements for structural applications.

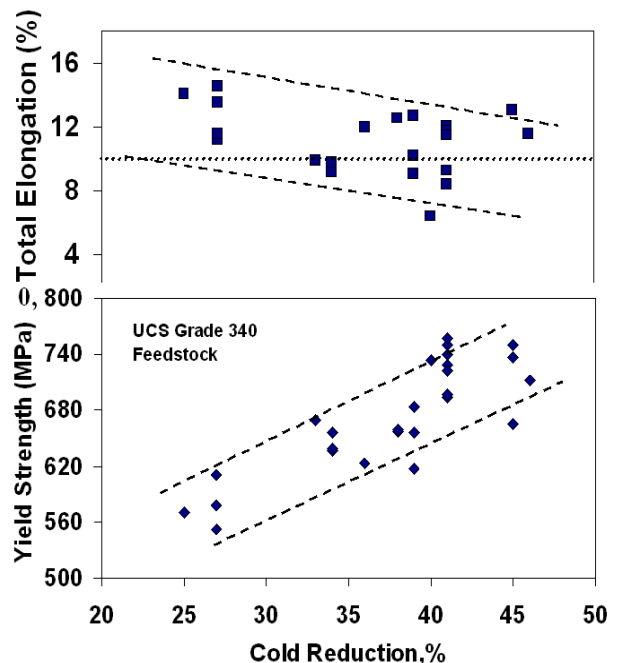


Figure 18. Effect of cold reduction on the mechanical properties of cold rolled recovery annealed UCS products. Gauge length 80mm.

6. SUMMARY

The CASTRIP facility at Nucor's Crawfordsville, Indiana plant has produced a range of commercial and structural UCS products. The coarse austenite grain size produced in the recent as-cast strip has led to final microstructures that are considerably different to conventional hot and cold rolled strip products. The inclusion engineering applied to facilitate strip casting by the CASTRIP process also produces inclusions that assisted with the final microstructure development by promoting particle-stimulated nucleation of intragranular acicular ferrite. From the experiences gained to date, it would seem that the tensile properties are generally consistent with what would be expected from the UCS microstructure and the behaviour in a range of formability tests is also reasonably consistent with the measures of formability such as the strain hardening index and the normal anisotropy. In comparison to some standard commercial structural quality thin hot and cold rolled grades, the UCS products exhibit lower total elongations but are more isotropic and display superior stretch flange-ability. While it is necessary and understandable to draw comparisons between new and conventional products, the newly developed UCS products offer their own unique suite of attributes. The challenge now becomes how to

exploit the strengths and opportunities provided by this new product type.

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