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Development of a family of high strength low carbon microalloyed ultra-thin cast strip products produced by the CASTRIP® process

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Keywords

produced, products, strip, cast, ultra-thin, microalloyed, carbon, low, development, strength, family, high, process, castrip®

Disciplines

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Development of a Family of High Strength Low Carbon Microalloyed Ultra-Thin Cast Strip Products Produced by the CASTRIP® Process.

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Keywords: Twin roll strip casting, niobium, microalloying, HSLA steels, age hardening.

Abstract

The manufacture of high strength strip products in strip thicknesses less than 1.5mm is very challenging for the conventional hot and cold rolled processing routes. A range of Nb and Nb/V microalloyed steels have been successfully strip cast by the CASTRIP® process enabling the development of a range of high strength Ultra-Thin Cast Strip (UCS) products. It was found that the CASTRIP process fully exploits the strengthening potential of the low C-Mn-Nb-(V) alloy design system. Substantial strengthening by microstructural hardening was provided by Nb. Retention of Nb and V in solid solution in hot rolled coils enabled further strengthening by a subsequent age hardening heat treatment. This paper describes the development of a range of high strength low alloy (HSLA) UCS products produced by the CASTRIP process, utilising a low C-Mn-Nb-(V) alloy system, covering yield strengths in the range of 350-550 MPa, in strip thicknesses of 0.9-1.5mm, for both the as rolled and hot dip galvanised coated conditions.

Introduction

The CASTRIP® facility at Nucor Steel's Crawfordsville, Indiana plant is the world's first commercial installation for the production of Ultra-Thin Cast Strip (UCS), via twin-roll strip casting. Several commercial and structural grades are in regular production, with strength levels up to ASTM A1039M SS Grade 380, in strip thicknesses in the range of 0.9mm to 1.5mm.

The manufacture of high strength (400-550 MPa YS) strip steel products in strip thicknesses less than about 1.5mm is difficult using conventional hot and cold rolling processing routes. High mill loads restrict the minimum strip thickness and maximum strip width availability of high strength hot rolled strip. The CASTRIP process has enabled the thickness range for hot rolled strip products to be extended down to about 0.8mm. A family of high strength low alloy (HSLA) hot rolled strip UCS products, has now been developed offering yield strength levels up to 550 MPa in the strip thickness range of 0.8-1.5mm, for both the hot band and hot dip galvanised coated product types.

Modern high quality, high strength, hot rolled strip grade designs are usually based upon the generic steel design known as high strength low alloy (HSLA) steels. This steel type is characterised by a low C, low carbon equivalent alloy design and utilises microalloying with Nb, V and Ti, either singly or in various combinations, coupled with thermo-mechanical controlled processing. Strengthening is achieved in these steels mainly via ferrite grain refinement and precipitation hardening. However, high mill rolling loads during thermo-mechanical processing of microalloyed HSLA steels curtail the minimum strip thickness and maximum strip width availability. Accordingly, the HSLA alloy design has been investigated in UCS steels produced by the CASTRIP process to extend the thickness range of hot rolled HSLA grades. The near net shape casting of twin-rolled strip casting does not enable conventional thermo-mechanical controlled processing strategies to be applied. However, in contrast to the conventional HSLA steel approach, UCS steels are able to utilise different strengthening mechanisms by exploiting a hitherto unexplored regime of rapid solidification, coarse austenite grain size and low hot rolling reductions. This paper presents the behaviour and strengthening mechanisms of Nb, V and Nb/V microalloyed UCS steels produced by the CASTRIP process and describes the mechanical properties of these high strength UCS products.

The CASTRIP® Process and Experimental Procedure

The CASTRIP twin-roll strip casting process 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 Nucor Steel's CASTRIP facility in Indiana are schematically 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 casting speed is typically in the range of 60-100m/min and the as-cast strip thickness is typically 1.8mm or less. The in-line hot rolling mill generally applies reductions in the range of 10 to 50%. On the run-out-table (ROT) there is a water cooling section utilizing air mist cooling to control the cooling rate through the austenite transformation. Further details of the CASTRIP process have been reviewed elsewhere[1,2].

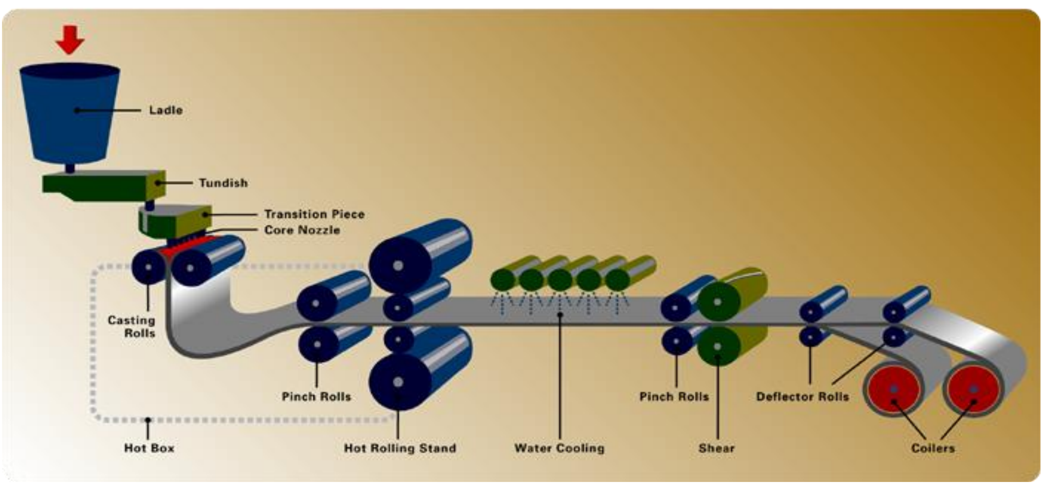


Figure 1 Main components of the CASTRIP process.

The steel type used for the grades in current production is a low-carbon-manganese-silicon steel; see the base grade in Table 1. Recently, a range of Nb, V and Nb/ V microalloyed UCS steels were successfully strip cast by the CASTRIP process. The compositions of the developmental steels are given in Table 1. The Nb levels were systematically varied from 0.014% to 0.084% with Mn levels in the order of 0.8% (Steels A-G), while a series of steels with about 0.06% Nb were produced with a range of Mn levels from 0.8% up to about 1.3% (Steels L-N). Trial steels with 0.04% V (Steel H) and 0.04% Nb and 0.04% V (Steel I) were also produced to complement the 0.04% Nb trial steel (Steel D), thus enabling the behaviour of the three microalloying systems in UCS products produced by the CASTRIP process to be compared. Each of the trial steels were in-line hot rolled to final strip thicknesses in the range of 1.0mm to 1.5mm, with reductions up to about 40%. The hot rolling was performed in the austenite temperature range, with rolling mill exit strip temperatures above 850°C. Accelerated cooling was applied on the run-out table (ROT) to achieve coiling temperatures in the range of 500°C to 650°C. Pickled material was hot dipped galvanised using a continuous hot dip galvanising line at Nucor's Crawfordsville plant. The strip temperatures utilised in the heat treating sections were selected to affect age hardening by Nb and V.

The microstructure of the final product was examined using optical microscopy, a JEOL© 200kV Scanning Transmission Electron Microscope (STEM) and an Imago LEAP™ atom probe tomography (APT). Laboratory age hardening heat treatments were carried out using an electric resistance heated continuous annealing simulator. Time-temperature thermal cycles were designed to simulate the heating rates in the annealing furnaces of a continuous hot dip galvanising line, for a range of peak temperatures and times. The austenite transformation behaviour for a range of the developmental Nb microalloyed steels was determined using a Theta Industries, Inc. Quench Dilatometer. The assessment of the mechanical properties of the final UCS products included uniaxial tensile tests, 180° bend tests, double 180° bend tests, low temperature 180° bend tests and hole-expansion tests.

Table 1 Compositions of the base grade, high Mn and microalloyed trial UCS products, 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	0.033	**1.28**	0.21	<0.003	<0.003	<100
K	0.039	**0.97**	0.15	**0.052**	**0.03**	60
L	0.025	**1.07**	0.20	**0.072**	<0.003	50
M	0.036	**1.2**	0.21	**0.056**	<0.003	40
N	0.037	**1.25**	0.19	**0.058**	<0.003	80

Effect of Niobium on the Decomposition Behaviour of Austenite

Continuous Cooling Transformation Diagram

The construction of a Continuous Cooling Transformation (CCT) diagram is a technique to estimate the influence of alloy additions on the austenite transformation and decomposition behaviour of steels. A range of the Nb steels (Steels A to G) were utilised in the study as well as the plain C base steel. Specimens were heat treated at 1250°C for 3 minutes to dissolve the microalloying elements and achieve the desired large austenite grain size (~100-120μm), simulating the relatively course austenite grain size as produced by the CASTRIP process.

Samples were cooled at controlled, continuous cooling rates through the austenite (γ) to ferrite (α) transformation. The transformation temperatures were taken at the changes in slope of the dilation curves using the usual technique. Full details of the dilatometery experiments are not recorded here, only a summary of the effect of Nb on the austenite transformation start and finish temperatures is presented.

Figure 2a summarizes the transformation start (Ts) and transformation finish (Tf) temperatures as a function of cooling rate for a C-Mn base UCS steel and the 0.014% Nb and 0.084% Nb experimental microalloyed UCS steels. The results for the other Nb levels were within the range for these two Nb levels. The Bainite start temperature (Bs), calculated from an empirical formula based on the steel composition[3] (Equation 1), is included; the line indicates the maximum temperature at which lower transformation products can transform.

$$Bs(°C) = 830 – 270C – 90Mn – 37Ni – 70Cr – 83Mo \qquad (1)$$

The Ts temperatures are replotted as a function of cooling rate in Figure 2b, to more clearly show the effect of Nb on depressing the Ts. From Figures 2a and 2b, it can seen that the Nb additions had only a small influence on the Ts at cooling rates up to 10°C/s, where sufficient time was available for the transformation of allotriomorphic ferrite at the prior austenite boundaries to occur. At higher cooling rates, a substantial influence of Nb on hardenability was recorded, even for a small Nb addition; a significant decrease in the transformation temperature occurred at 30°C/s for the 0.014% Nb UCS steel and at 20°C/s for the 0.084% Nb UCS steel. The Ts temperature for the Nb grades were relatively constant at cooling rates of 30°C/s and higher, indicating that the nose of the ferrite C-curve was shifted to the right and the bainite C-curve was relatively flat for this cooling rate range. Bainite typically has a flat-topped C-curve with a sharp nose as the martensitic transformation is approached. The UCS steels in this study are low alloy steels and as such martensite was not observed with optical microscopy, even at a cooling rate of 100°C/s. The addition of Nb also depressed the transformation finish temperatures in comparison to the plain C base grade, especially at intermediate to high cooling rates; this essentially correlated with the delayed Ts temperatures.

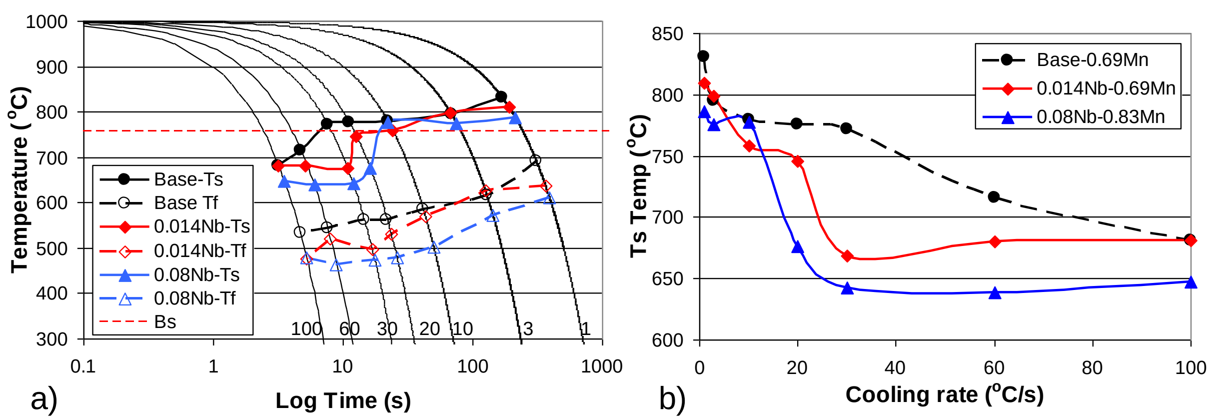


Figure 2 a) CCT diagram as a function of cooling rate (°C/s) showing the influence of niobium on the (Ts) and (Tf) temperatures and b) Ts temperature plotted at a function of cooling rate, for C-Mn-(Nb) UCS products.

The decrease in Ts temperature can be attributed to Nb suppressing the transformation of allotriomorphic ferrite at the prior austenite grain boundaries. For a cooling rate of 30°C/s the plain C base steel was predominately polygonal ferrite intermixed with low carbon bainitic ferrite. At the same cooling rate, both the Nb UCS steels showed fully bainitic microstructures, with the microstructure being slightly finer for the higher Nb steel. Even 0.014% Nb in a relatively lean alloy level steel raised the hardenability sufficiently to allow a fully bainitic microstructure to be formed at cooling rates of 30°C and higher. Such cooling rates are readily achievable for the cooling of thin strip on the ROT. Importantly, these cooling rates are likely to underestimate the actual hardenability of the of the Nb UCS steels, as although the austenite grain size in the dilatometery specimens was relatively large at 100-120µm, it was still finer than the actual as-cast austenite grain size (150-250µm).

The 0.084% Nb UCS steel predominantly displayed lower Ts and Tf temperatures compared to the 0.014% Nb steel. The Mn content was however, slightly higher in the 0.084% Nb steel, which based upon equation 1, would account for about half the difference in the Ts temperatures. At the alloy content and austenite grain size of the UCS steels investigated, a relatively small addition of Nb produced a significant increase in hardenability, while increasing Nb levels resulted in only a modest further increase in hardenability.

Transition Coil Hardening Effects

Given the potent effect of small Nb additions on hardenability based on laboratory dilatometer studies, the effect of Nb additions on the austenite transformation behaviour was evaluated via a controlled industrial scale trial by examining 'compositional transition' coils. The developmental Nb microalloyed steels were sequentially cast after a plain C UCS steel of similar composition, which generated a 'compositional transition' coil containing a gradient in the Nb content. The casting and processing conditions were held constant through the compositional transition coils, so that the effect of increasing Nb content on strength and final microstructure, particularly at low levels of Nb (<0.015%), could be progressively assessed. The results of the evaluation of the transition coils for two 0.015% Nb heats and the 0.084% Nb heat (Steel G) are presented in Figure 3.

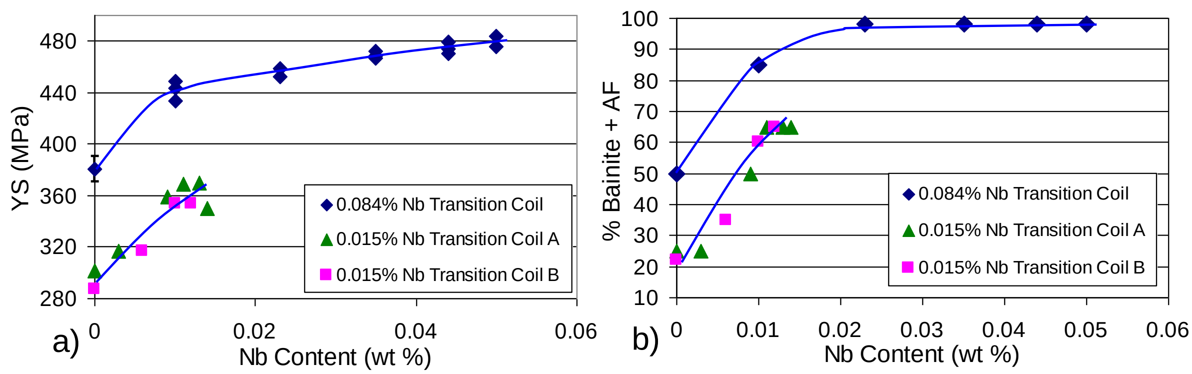


Figure 3: Influence of Nb content on a) the yield strength and b) the final microstructure[4].

The effect of increasing Nb content on the yield strength is shown in Figure 3a for the three coils. For the 'compositional transition' coil associated with the 0.084% Nb UCS steel (Steel G), there was a substantial initial yield strength increase of about 60 MPa to 440 MPa with 0.01% Nb and thereafter the strength level continued to progressively increase, but at a lower rate, to about 480 MPa at 0.05% Nb. A very similar strengthening response was displayed by the two low Nb transition coils, where a 60 MPa increase in the yield strength was recorded from a

0.01% Nb addition. The effect of Nb content on the final microstructure formed is shown quantitatively in Figure 3b, in terms of the proportion of acicular ferrite/bainite phases present in the final microstructure. It can be observed that the increase in yield strength corresponded to the increased bainite/acicular ferrite content for both Nb levels. Typical microstructures at various Nb levels from the 0.084% Nb transition coil are shown in Figure 4.

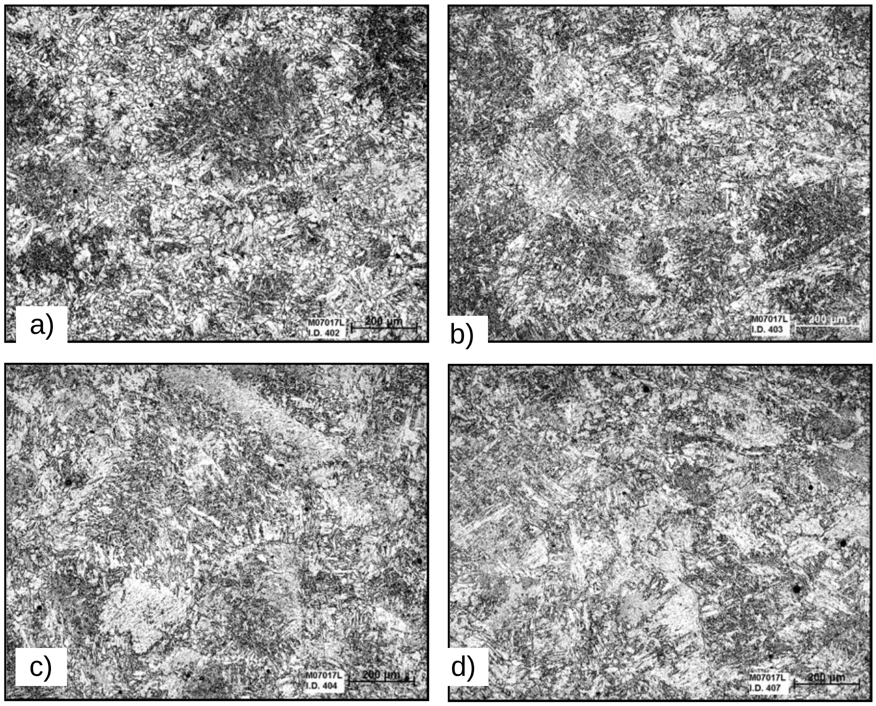


Figure 4: Typical microstructures observed from the 0.084wt% Nb coil, where the Nb content was, a) <0.003%, b) 0.01%, c) 0.023% and d) 0.05%.

For the recently produced plain C UCS steel (without Nb) the microstructure consisted of allotriomorphic ferrite and acicular ferrite, Figure 4a. A significant reduction in the proportion of allotriomorphic ferrite and a refinement of the microstructure occurred even with 0.010% Nb (Fig. 4b) in this UCS product, accounting for the substantial initial strength increase recorded. At the 0.023% Nb level in this UCS product (Fig. 4c), the allotriomorphic ferrite formation was suppressed and replaced with bainite. This outcome was consistent with the microstructural changes observed in the dilatometer study. With continuing increases in the Nb content, Fig. 4d, the proportion of bainitic phases increased and the volume fraction of acicular ferrite diminished. The increasing proportion of bainite and reduced proportion of acicular ferrite with increasing Nb may be due to the progressive suppression of allotriomorphic ferrite by the Nb addition enabling bainite to nucleate from the austenite grain boundaries. As austenite grain boundaries are a lower energy site for nucleation than intra-granular nucleation of acicular ferrite at inclusions, bainite could be expected to progressively displace acicular ferrite with increasing Nb content[3]. After the allotriomorphic ferrite was replaced with bainite, the progressive strength increment recorded in the Nb UCS steel with further increases in Nb content was most likely accounted for by the progressive refinement of the microstructure.

The CCT study and the evaluation of compositional transition coils have both shown that Nb provides a substantial increase in hardenability. Even relatively small additions of Nb were found to suppress allotriomorphic ferrite formation, allowing bainite to nucleate, providing substantial strengthening at cooling rates readily achievable during ROT cooling of thin strip. In addition, it has been previously reported[4] that austenite recrystallisation is suppressed in Nb microalloyed UCS following in-line hot rolling, see Figure 5. The suppression of austenite recrystallisation in Nb microalloyed UCS results in the retention of the coarse as-cast austenite grain size, further aiding the hardenability of Nb UCS steels. The effect of retained strain and shear band formation on reducing hardenability seems to be more than offset by the potent hardening capacity of Nb. The development of the final strip microstructure in Nb microalloyed UCS steels compared with recent plain C UCS steels is summarised schematically in Figure 6.

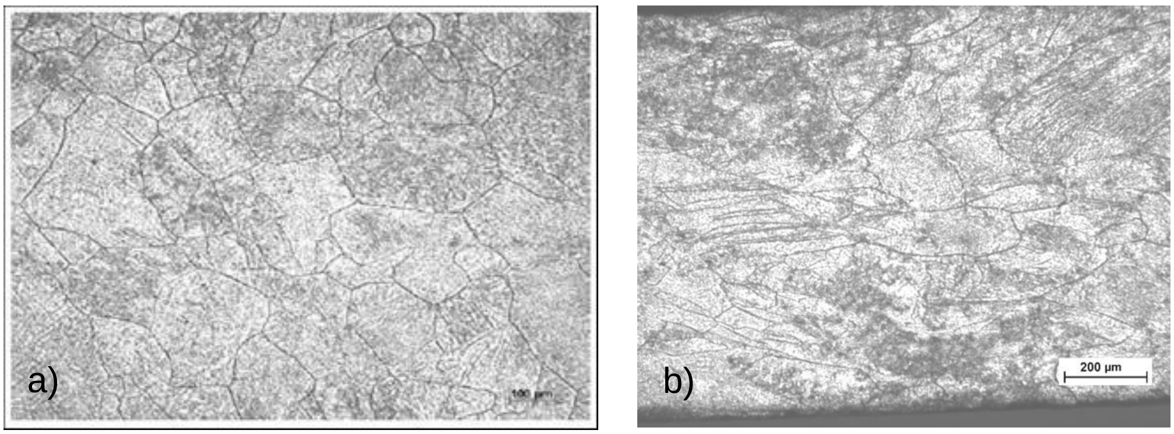


Figure 5: Unrecrystallised austenite grains in Nb Steel F after a) 15% hot reduction and, b) 35% hot reduction.

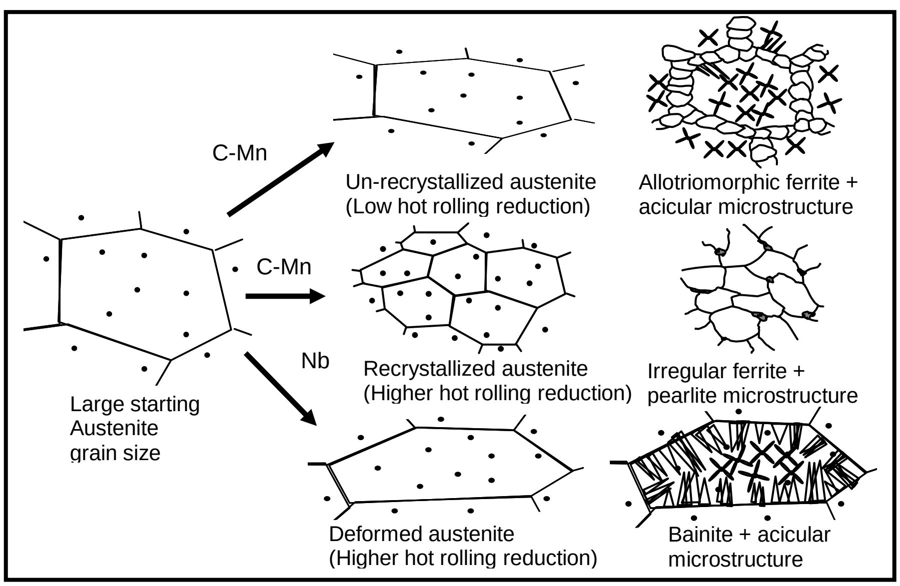
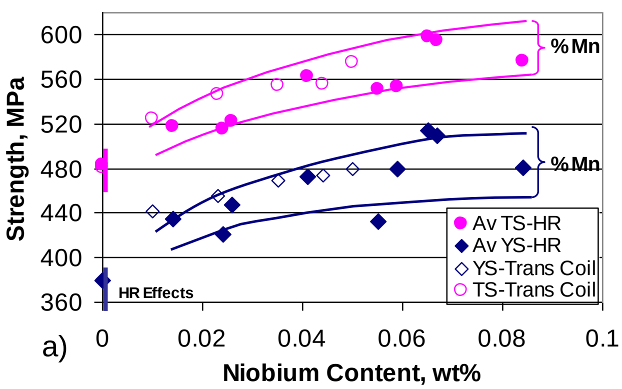


Figure 6: Schematic showing development of typical microstructures in UCS; C-Mn with low hot rolling and no austenite recrystallisation, C-Mn with higher hot rolling and austenite recrystallisation and C-Mn-Nb microalloyed grades with no austenite recrystallisation at higher hot rolling reduction.

Tensile Properties of Nb Microalloyed UCS Steels

The average yield and tensile strength results, for each of the initial trial Nb microalloyed UCS steels (Steels A to G), are presented in Figure 7a, where strength levels initially increased sharply for low levels of Nb (<0.02%) and thereafter increased progressively. The bands shown for the yield and tensile strengths reflect that there were slight, but significant, differences in Mn content (0.72% to 0.87% Mn) between the steels. The higher Mn steels achieved strength levels at the top of the band, while the lower Mn steels recorded strengths towards the bottom of the band. Overall, the results showed that a 415 MPa UCS product can be achieved using a small addition of Nb and a 450-480 MPa UCS product can be achieved with higher Nb levels. The yield strength results from the 'compositional transition' coil produced with Steel G, given previously in Figure 3a, are also included in Figure 7a for comparison. The collective average yield strength results for the individual developmental steels and the transition coil are in close agreement, which confirms the repeatability of the strengthening effect of Nb. Thus, the addition of Nb to UCS steels substantially expanded the range of tensile properties achievable from the plain, low C, low carbon equivalent steels studied, while providing the basis for a range of thin hot rolled HSLA UCS grades.



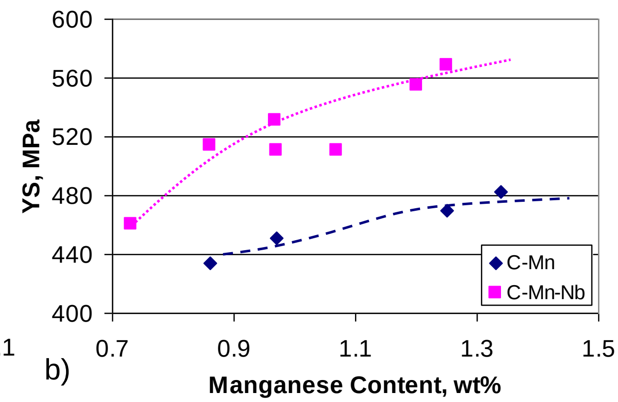


Figure 7a) Effect of increasing Nb on strength of UCS microalloyed grades where the Mn varied from 0.67 to 0.9 wt% (included on the graph are results from a transition coil on to a Nb grade). b) The influence of increasing Mn content on the yield strength of C-Mn and C-Mn-Nb grades, where the Nb varied from 0.058 to 0.072 wt%.

Metallographic examination of the various developmental Nb microalloyed UCS steels found the change in microstructure with increasing Nb content to be consistent with that observed from the transition coil study; a predominately bainite and acicular ferrite microstructure that was devoid of substantial grain boundary ferrite, while the proportion of bainite increased and was progressively refined, as the Nb content increased. Transmission electron microscopy (TEM) examination of two Nb microalloyed UCS steels (steels C and F) did not reveal evidence of Nb precipitation[4]. Further examination of the Nb UCS steels using the atom probe tomography technique also did not reveal any evidence of Nb precipitation and indicated that Nb was retained in solid solution[5]. Thus the strengthening observed from microalloying with Nb can be mostly attributed to microstructural hardening. This occurs directly through increasing the hardenability and indirectly by retaining the coarse as-cast austenite grain size through suppression of austenite recrystallisation following in-line hot rolling. The retention of Nb in solid solution, rather than forming a precipitate, can be attributed to the following factors:

i) Rapid cooling rate during solidification that avoids the formation of large interdendritic Nb rich precipitates commonly formed in both thick and thin continuously cast slabs[6].

ii) Single hot rolling pass of limited total reduction and the short time interval before ROT cooling starts, suppresses strain induced precipitation of Nb, which usually occurs during rolling of hot rolled strip.

iii) The enhanced hardenability imparted by Nb in solid solution suppresses grain boundary ferrite formation, promoting the acicular ferrite and bainitic transformations. As such, transformation start temperatures are too low to enable Nb precipitation to occur in a continuous cooling environment such as the ROT of the CASTRIP process.

Given the significant effect on strength of modest changes in Mn content (Figure 7a), a series of 0.06% Nb UCS steels and plain C UCS steels with a range of higher Mn levels, up to about 1.3% Mn, were strip cast. The strength results are presented as a function of Mn content in Figure 7b for both the plain C and Nb UCS steels, showing that raising the Mn content provided significant additional strengthening in both the plain C and Nb microalloyed UCS steels. The strengthening increment provided by Nb was little affected over the range of Mn levels assessed, enabling yield strength levels of over 550 MPa to be recorded for Mn levels of about 1.25%. Thus the low C, lean carbon equivalent, Mn-Nb UCS steels produced provided the basis for manufacturing very thin, hot rolled HSLA steel grades, achieving strength levels ranging from 350 MPa to 550 MPa.

In respect to ductility, the total elongation results associated with the developmental steels presented in Figures 7a and 7b, are given in Figure 11b as a function of the tensile strength for the steels. Ductility decreased progressively with increasing strength as would be expected. Importantly, the total elongation values exceeded the ductility requirements in ASTM A1039 for HSLA grades up to 550 MPa.

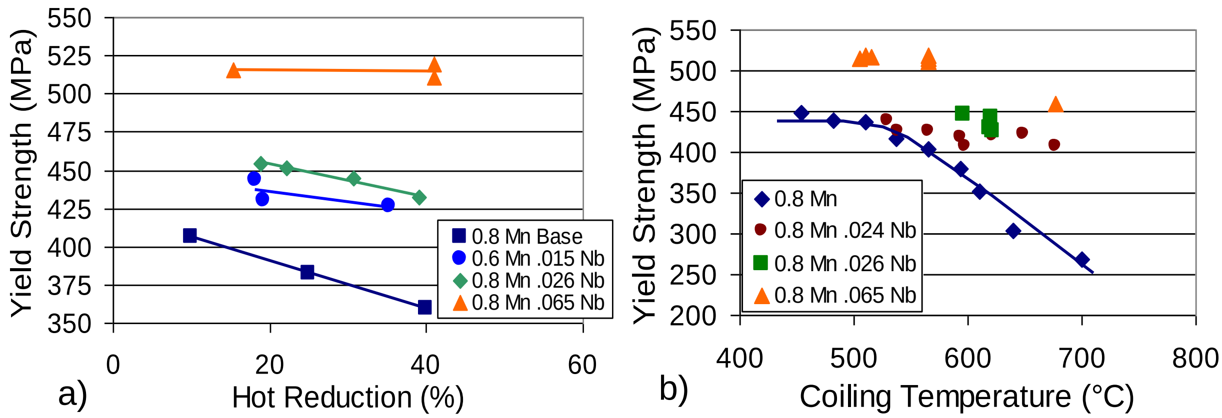


Figure 8a) Effect of hot reduction on yield strength and b) Effect of coiling temperature on yield strength of the C-Mn-Si base UCS steel and various Nb microalloyed UCS steels[4].

The effects of in-line hot reduction and ROT accelerated cooling conditions on the strength levels of the Nb UCS steels were extensively evaluated during the plant trials, the results of which are summarised in Figure 8 and have been reported elsewhere[4]. In contrast to the plain C base steel, the strength level of the Nb UCS steels was insensitive to the degree of in-line hot rolling reduction, at least up to 50% (Figure 8a), and to coiling temperatures in the range of about 500°C to 650°C (Figure 8b). This response of the Nb UCS was attributed to the enhanced hardenability provided by Nb and suppression of austenite grain refinement[4]. This attribute enables high strength levels to be achieved across the full strip thickness range produced by the Castrip process, while also providing a wide operational coiling temperature range.

The composition of the trial steels microalloyed with V and Nb + V are listed in Table 1. The effect of V in hot rolled UCS steels has been previously reported[7] and was found to not provide any significant strengthening in UCS hot band for 0.04% V UCS hot rolled steel. Furthermore, the addition of V to a Nb UCS steel did not provide any additional strength benefit over a comparable Nb only UCS steel in the hot rolled condition.

Laboratory Age Hardening Results

As noted previously, the TEM and APT examinations of the Nb microalloyed UCS trial steels did not reveal any Nb precipitation in the hot rolled condition, and the ATP results showed the Nb to be retained in solid solution, thus making it available for subsequent strengthening by an age hardening heat treatment. To investigate the potential age hardening characteristics of the Nb UCS steels, laboratory age hardening heat treatments were undertaken on a range of the Nb UCS trial steels. Short time heat treatments were carried out using an electric resistance heated continuous annealing simulator, utilising a time-temperature cycle to simulate the annealing section of a continuous hot dip galvanising line for a range of peak temperatures and three hold times at the peak temperature of 0, 10 and 20 seconds.

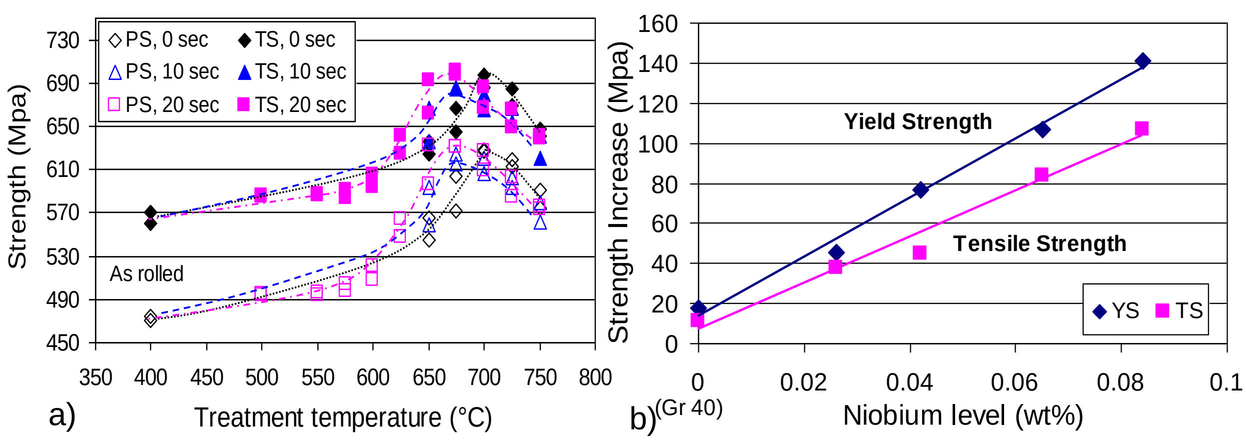


Figure 9 Laboratory age hardening of Nb UCS steels. a) Effect of temperature peak and holding time on strengthening response for a 0.084% Nb UCS steel and. b) Strength increase between the hot rolled and maximum age hardened strengths as a function of Nb level[4].

The response of the 0.084% Nb UCS steel (steel G) to an age hardening heat treatment is given in Figure 9a. The yield strength follows a typical age hardening response; strengthening began at about 625ºC, maximum strengthening occurring in the temperature range of 675 to 725ºC and over ageing occurred thereafter. The maximum strength increment was about 150 MPa, producing yield strengths of over 600 MPa. The temperature for peak strengthening was slightly higher for the shortest hold time, though the results for 10 and 20 seconds were similar, indicating the strengthening response was not overly sensitive to time at temperature. TEM examinations of samples heat treated in the over ageing temperature regime (750ºC), where particle coarsening would be expected to aid identification, found very fine Nb rich precipitates in the size range of 4-15 nm, indicating the observed strengthening increment was due to an age hardening process.

A similar heat treatment programme was applied to a range of the trial Nb UCS steels and Figure 9b summarises the age hardening response, where the maximum strength increment is presented as a function of the Nb content of the steel. The results showed a progressive increase in the age hardening strengthening increment with increasing Nb level, indicating the required strength can be controlled via the Nb content of the UCS steel. The actual strengthening increment provided by Nb age hardening maybe somewhat higher than the observed outcomes in the heat treated samples, as microstructural restoration processes in the acicular ferrite/bainite microstructure may have partially offset the strengthening by Nb age hardening mechanisms[8], Moreover, the small strength increase recorded for the plain C, low strength base UCS steel of this study, suggested an additional strengthening contribution from carbon dissolution and retention in solution. Ultimately, the resultant strength increment from age hardening was very significant and strongly correlated with the Nb content of the UCS steel.

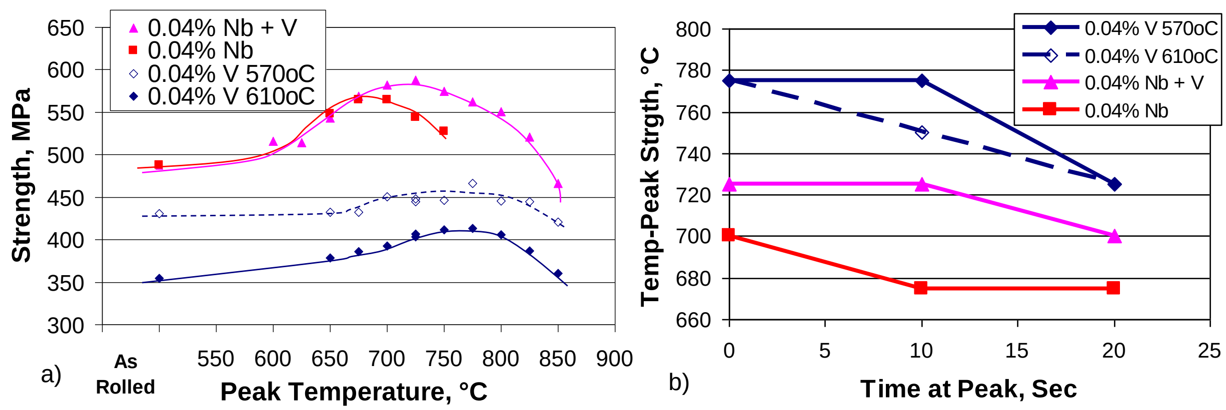


Figure 10 Laboratory aging results for V, Nb and V + Nb steels for a) strength as a function of peak aging temperature (10 sec at peak temp.) and b) temperature for peak strength as a function of time at peak temperature.

The response of the 0.04% V (Steel H) and 0.04% Nb + 0.04% V (Steel I) trial UCS steels to age hardening heat treatments was also evaluated using the laboratory continuous annealing simulator. The results are summarised in Figure 10, with the results for the 0.04% Nb (Steel D) UCS steel also included for comparison. Figure 10a showed the effect of the peak heat treatment temperature on the strength of three microalloyed UCS steels for a single dwell time at the peak temperature, while Figure 10b presents the peak temperature that produced the highest strength as a function of the dwell time at the peak temperature. The following observations can be drawn from the heat treatment results:

i) The response of the 0.04% V UCS steel indicates that the age hardening temperature peak occurred at a higher temperature than for the 0.04% Nb UCS steel,

ii) The temperature for peak strengthening for the Nb/V UCS steel was intermediate between the Nb and V UCS steels.

iii) The width of the temperature range for peak age hardening was greater for the Nb/V UCS steel than the Nb and V UCS steels,

iv) The wider temperature range for peak age hardening exhibited by the Nb/V UCS steel probably reflects the differing, but overlapping, age hardening temperature peaks for Nb and V UCS steels.

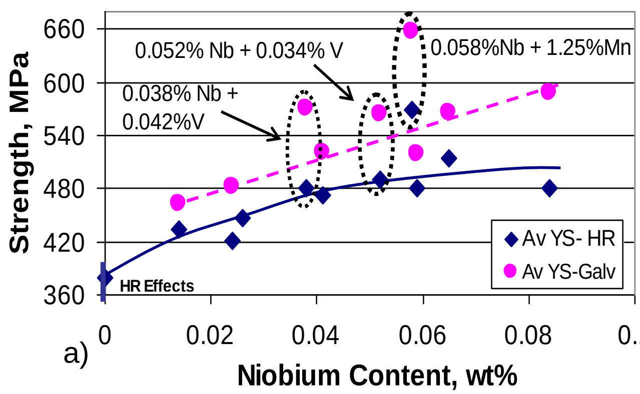
v) The strength increase produced from age hardening the Nb + V steel was approximately equivalent to the sum of the peaks strength increases recorded for the 0.04% Nb and 0.04% V steel (570°C).

vi) The strength increase for the V steel was greater in the higher CT product, probably reflecting less microstructural softening compared with the lower CT material, to offset the strengthening from age hardening.

vii) The greater width of the temperature range for peak age hardening for the dual Nb/V microalloying system suggests such an alloy design would provide a broader processing window for applying an age hardening heat treatment in a continuous strip processing environment.

Tensile Properties of Age Hardened and Galvanised Microalloyed UCS Steels

The age hardening response of Nb and V UCS steels observed in the short time heat treatments indicated the potential for age hardening these steels using a continuous annealing line or the annealing section of a hot dip continuous galvanising line. Subsequent plant scale trials were conducted on the continuous hot dip galvanising line at Nucor's Crawfordsville plant to age harden the Nb, V and Nb/V UCS steels, utilising processing conditions derived from the laboratory ageing studies. The results from the full scale production trials are summarised in Figure 11a for a range of the Nb UCS steels, two Nb/V UCS steels (Steels I and K) and the 0.058% Nb + 1.25% Mn (Steel N) higher strength grade. Significant and consistent strengthening was observed using the short heat treatment cycle applied using the annealing furnaces of the hot dip continuous galvanising line.



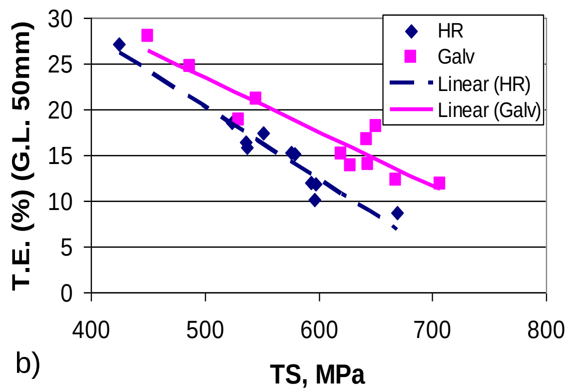


Figure 11a) Yield strength as a function of Nb content for hot-rolled and galvanised CASTRIP and b) Tensile strength verses total elongation for hot rolled and galvanised C-Mn and C-Mn-Nb UCS product.

The final strength levels recorded were similar to that produced with the laboratory heat treatments of the respective microalloyed UCS steels. Final strength levels of over 450 MPa were recorded with the 0.024% Nb UCS steel (Steel B), over 500 MPa with 0.04%Nb (Steel D) and over 550 MPa with the higher Nb UCS steels (Steels F & G). For the 1.25% Mn UCS steel (Steel N), with higher yield strength levels in the as hot rolled condition, an age hardening strength increment of about 100 MPa was still realised, resulting in yield strengths in the region of 650 MPa being recorded. The dual Nb/V microalloyed UCS trial steels exhibited a greater age hardening strength increment then the Nb microalloyed steels with comparable Nb content. This outcome is consistent with the laboratory heat treatment results and supports the contention that Nb and V provided additive age hardening strength increments. Hence the dual Nb/V microalloying approach provides an attractive alloy design for age hardened and galvanised UCS products. These outcomes indicate 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. In particular, the capability to provide a range of high strength grades up to and including a 550 MPa grade, with an aged hardened, low C, lean carbon equivalent, microalloyed UCS steel has been demonstrated.

With regard to ductility of the age hardened and galvanised Nb UCS products, the total elongation results are presented in Figure 11b as a function of tensile strength, along with the results for the as-hot rolled condition. Total elongation values of over 10% were achieved for tensile strengths up to 700 MPa, and overall the results easily comply with the ductility requirements of current product standards for UCS material (ASTM A1039 and A1063). Importantly, the results showed that the tensile strength-total elongation relationship for the age hardened and galvanised UCS products was not an extension of the relationship for the hot rolled condition, but the age hardened and galvanised products offered an improved tensile strength-total elongation combination.

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 galvanised condition than for the as-hot rolled UCS products. The microstructural changes that have produced this outcome are still under investigation, but it is proposed that it was a resultant of microstructural restoration processes in the high dislocation density acicular/bainite structures combined with strengthening mechanisms by Nb rich clusters/precipitates. This provides the basis for offering high strength galvanised microalloyed UCS products with excellent ductility in thin sheet steels.

Formability of High Strength Microalloyed UCS Products

The formability of the high strength microalloyed UCS products covering a range of strength levels was assessed by 180° bend tests, double 180° bend tests (‘handkerchief’ bend test), low temperature 180° bend tests. The results are summarised in Table 2 and examples of various bend tests are shown in Figure 12.

Table 2: Summary of transverse orientated bend test results. (P – Pass, BL –Borderline).

Steel	Condition	Thickness (mm)	YS (MPa)	Bend Radii			
				1.5 T	0 T	Double bend	0 T @ -75°C
Base	HR	1 – 1.45	275 – 435	12P	12P	4P	2P
Steel L	HR	1.25 – 1.4	500	6P	6P	4P	-
Steel D	Galv	1 -1.2	530	6P	6P	4P	-
Steel N	HR	1 – 1.2	565	6P	4P, 2BL	3P, 1BL	2P
Steel L	Galv	1.1 – 1.4	600	6P	6P	4P	2P
Steel N	Galv	1.2	660	3P	2P, 1BL	2BL	-

Bend test samples in the hot rolled and the age hardened and galvanised conditions, covering the full strength range produced, were successfully bent at 1.5T and 0T radii in the 180° bend test in the longitudinal and transverse bend axis orientations, at ambient and -75°C temperatures. The three transverse tests recorded as borderline at 0T were just discrete, fine, shallow surface tears. Double bend tests were successfully produced in all products, except for three borderline results for the thickest and strongest products, where again only discrete fine, shallow tears were observed. The bend test results confirm the ductility of these high strength products displayed in the tensile tests. It is likely that the small globular nature of the nonmetallic inclusions in the microalloyed UCS steels also assisted in the excellent bend test performance.

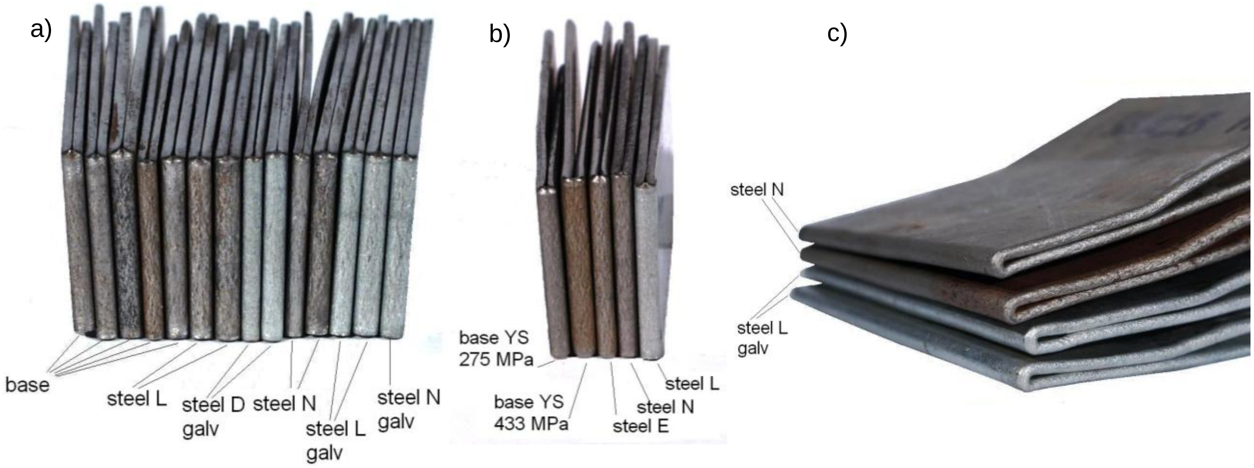


Figure 12 Typical examples of transverse 0T bend test for base grade and microalloyed UCS steel in hot rolled and galvanised conditions for a) room temperature, b) -75°C and c) double bend tests at room temperature.

The stretch-flangeability of the microalloyed UCS steels in the hot rolled and age hardened and galvanised conditions were tested using the commonly applied hole-expansion test. Results are presented in Figure 13 in comparison to the results for the plain low carbon UCS steels and some conventional hot rolled and cold rolled, continuously annealed structural quality grades of similar thicknesses.

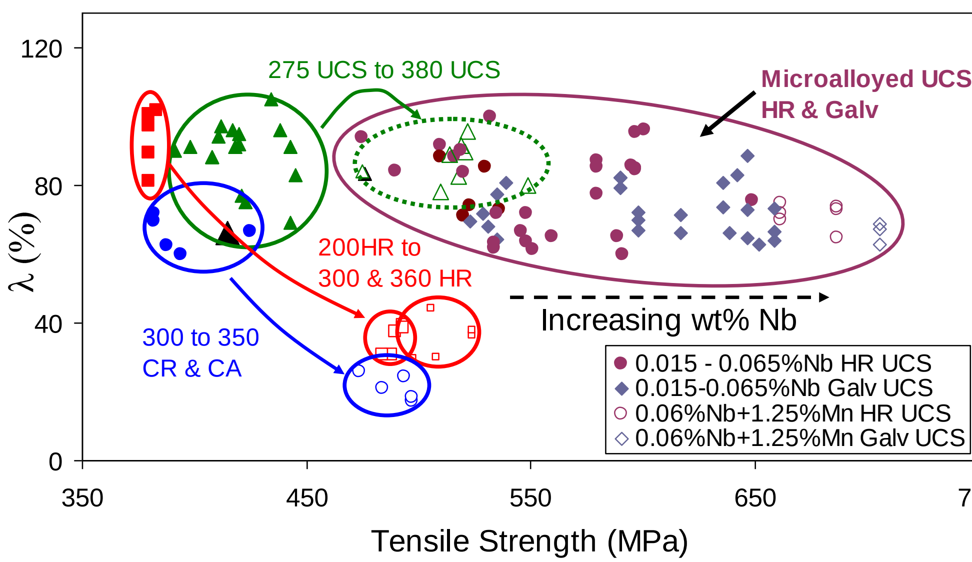


Figure 13 Stretch-flangeability as measured by the hole-expansion test as a function of tensile strength for the plain low C base grade and Nb microalloyed UCS products, compared to conventional hot rolled and cold rolled, continuously annealed structural quality strip grades.

The Nb microalloyed UCS steels produced displayed an excellent hole-expansion test performance over the full tensile strength range achieved; up to about 700 MPa. At the lower end of the tensile strength range (TS~500 MPa), the hole-expansion test performance was similar to the plain carbon 275 UCS steels that were cast and the low strength hot rolled grade (200 HR).

The hole-expansion performance decreased slightly with increasing strength, but was still substantially superior to conventional medium strength hot rolled (300 & 360 HR) and cold rolled and continuously annealed (300 & 350 CR & CA) structural grades, even at tensile strengths well above that of the conventional medium strength structural grades. The excellent hole-expansion test performance can be attributed to the refined bainite and acicular ferrite microstructure with a fine distribution of carbides in the Nb UCS steels, which provides a high degree of microstructural uniformity that assists microplasticity[9]. This property attribute is important to high strength steels for structural and component applications where forming of sheared edges is often required.

Summary

The evaluation of Nb, V and Nb/V microalloyed, low carbon, UCS steels has shown the capability to produce a range of high strength, light gauge steel sheet products with yield strength levels up to 550 MPa and potentially higher, with microalloyed UCS steels produced by the CASTRIP® process. The alloying and strengthening mechanisms are schematically summarised in Figure 14 and briefly described in the following:

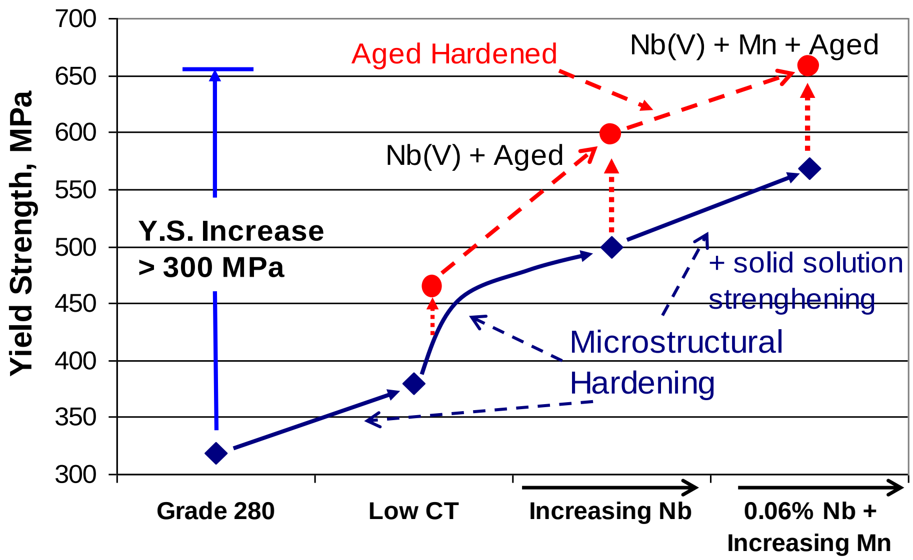


Figure 14 Schematic summary of alloying and strengthening mechanisms to achieve high strength UCS products.

i) Niobium provided significant strengthening in the as-hot rolled condition, predominately through microstructural hardening, via directly increasing hardenability and indirectly by suppressing austenite recrystallisation, retaining the coarse as-cast austenite grain size.

ii) Modest increases in the Mn content provided additional significant strengthening through solid solution hardening and further microstructural refinement, enabling the yield strength to be raised to over 550 MPa, providing in combination with Nb, the basis for a range of high strength hot band grades.

iii) The retention of Nb (and V) in solid solution provided the capability to achieve substantial strengthening from age hardening heat treatments, to further raise the strength above that achieved in the hot band. The age hardening strength increment was found to be a function of the Nb and V microalloying levels, so by adjusting these levels and in conjunction with modest Mn contents, yield strength levels in the age hardened and galvanised condition of up to 650 MPa were recorded. In addition, the ductility was not impaired by age hardening, resulting in an improved strength-ductility relationship compared to the hot rolled condition.

The results of extensive laboratory studies and plant scale trials has shown that microalloyed (Nb, V), low C and carbon equivalent, UCS steels produced by the CASTRIP process offer the capability to achieve a range of thin, high strength, (HSLA), hot rolled sheet steel grades. This capability significantly extends the strength/thickness range for hot rolled strip products.

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