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# Recent Product Developments with Ultra-Thin Cast Strip Products Produced by the CASTRIP® Process

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**Keywords:** Strip casting, microalloying, niobium, high strength sheet steel, age hardening

**Abstract:** Recent product development has focussed on developing a range of higher strength structural grades, covering the strip thickness range 0.9-1.5 mm, utilising Nb microalloying. A wide range of Nb levels have been successfully strip cast by the CASTRIP® process. Niobium was found to retard austenite grain refinement and substantially enhanced hardenability, which produced significant microstructural hardening and higher strength hot band. Niobium was retained in solid solution enabling further significant strengthening to be achieved from an age hardening heat treatment. Strength levels ranging from 400 MPa to in excess of 550 MPa, in combination with high ductility, were achieved in the age hardened and hot dip galvanised condition, utilising the annealing furnaces of a conventional hot dip galvanising line. The effect of microalloying content and processing conditions on the microstructure and final mechanical properties of Nb microalloyed UCS products produced by the CASTRIP process are described.

## Introduction

The CASTRIP®* facility at Nucor Steel's Crawfordsville, Indiana plant produces several commercial and structural grades, with strength levels up to ASTM A1011M SS Grade 380, utilizing a plain, low-carbon steel type. Recent product development has been directed at developing higher strength UCS grades (up to 550 MPa), in both the hot rolled and galvanised conditions to expand the product range of UCS products by investigating microalloying with Nb [1,2,3]. With conventional hot rolled strip, microalloying is coupled with thermo-mechanical processing involving multiple, high hot reductions, to achieve a refined ferrite grain size. In the case of UCS products, this conventional processing approach is not applicable. This paper investigates the behaviour of Nb in UCS steels, in a regime of a coarse austenite grain size and low hot rolling reductions, which has previously not been explored.

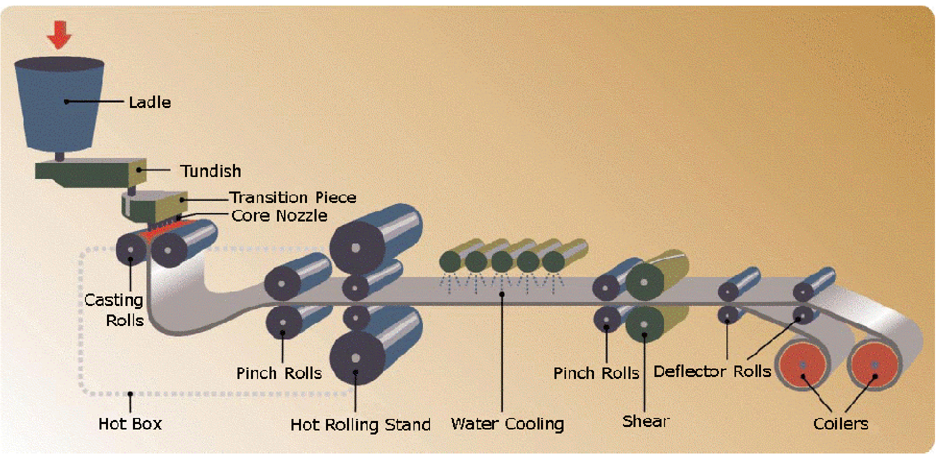



Fig. 1 Main components of the CASTRIP® process

* CASTRIP is a registered trade mark of Castrip LLC

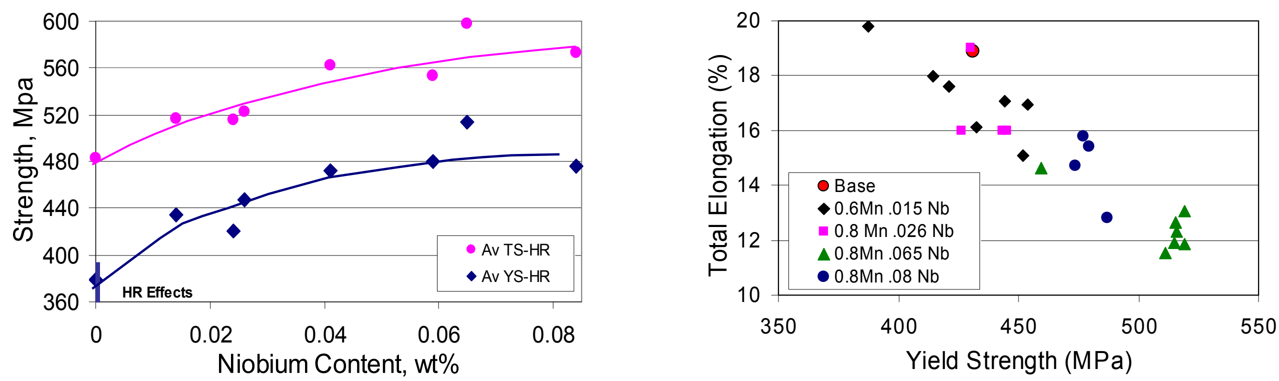
## Ultra-thin cast strip production via the Castrip process

The main components of Nucor Steel's CASTRIP facility are indicated in Fig. 1. The details of the process have been reviewed elsewhere [4,5], so are only briefly described here. The CASTRIP 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. A ladle feeds a large conventional tundish and then a smaller tundish or transition piece. The casting speed is typically in the range of 60-100 m/min and the as-cast strip thickness is typically 1.8 mm or less. The in-line hot rolling mill generally applies reductions of 10 to 50%, producing final thicknesses typically in the range of about 0.9-1.5 mm. On the run-out-table there is a water cooling section utilizing air mist cooling. Control of the cooling rates through the austenite transformation assists in achieving the desired microstructure and resultant mechanical properties of the UCS products.

## Higher strength microalloyed steels

The current range of plain low-carbon steels can achieve yield strength levels up to 380 MPa. Moreover, the thickness range for the higher strength grades, (340 – 380 MPa), can be limited because of the reduction in hardenability from austenite grain refinement during hot rolling [2].

A range of low C, Nb microalloyed steels have been successfully cast by the CASTRIP process with the Nb levels varied from 0.014 - 0.084 wt% with Mn levels in the range of 0.6 – 0.9 wt%. The final strip thicknesses produced were in the range of about 1.0 - 1.5 mm, with in-line hot rolling reductions ranging from 10- 40%. Niobium microalloyed UCS steels have been found to significantly extend the strength and thickness range potential for UCS products through suppressed austenite recrystallization, enhanced hardenability and age hardening mechanisms.




a) b)

Fig. 2 a) Effect of niobium content on the average yield and tensile strength of hot-rolled Nb UCS steels. b) The change in total elongation with yield strength for Nb UCS steels

**Tensile properties.** The average yield and tensile strength results, for each of the trial niobium microalloyed UCS steels, are presented in Fig. 2 (a). The strength level initially increased sharply for low levels of niobium and thereafter more gradually for niobium levels over about 0.02 wt%. In previous work, it was shown that strengthening in the niobium UCS product was primarily due to microstructural hardening; a predominantly bainite and acicular ferrite (AF) microstructure was observed which was devoid of substantial grain boundary ferrite [3]. The enhanced hardenability provided by niobium suppressed the formation of proeutectiod ferrite and promoted the formation of AF and bainite. By maintaining a larger austenite grain size in conjunction with the inclusion engineering practices, particle-stimulated intragranular nucleation of AF in the niobium microalloyed UCS steels can dominate the microstructure [3]. Furthermore, transmission electron microscopy (TEM) examination of the microalloyed steels did not reveal any evidence of niobium precipitation.

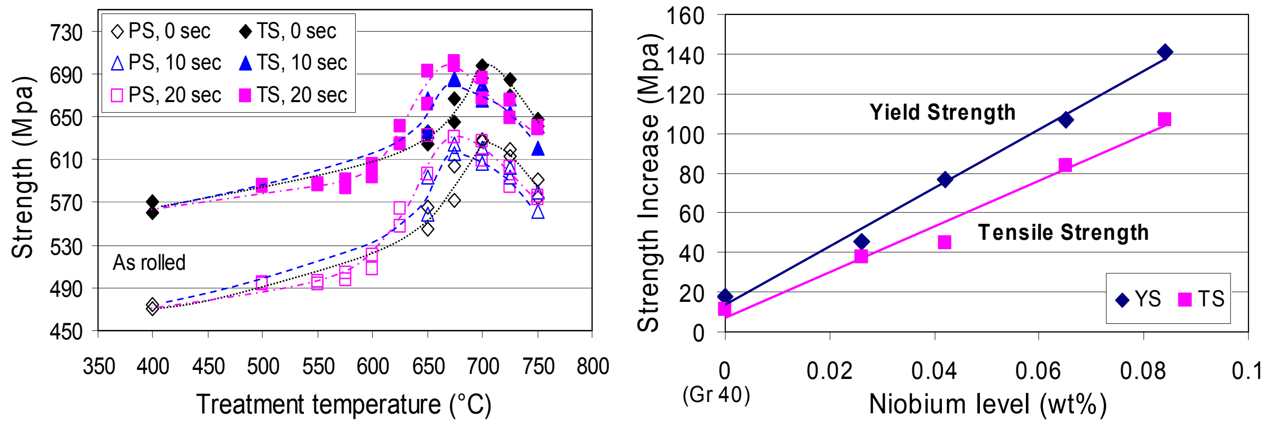
The total elongation results are presented in Fig. 2 (b) and it can be seen that the ductility continuously decreased as the yield strength increased. Importantly, even at yield strength levels over 500 MPa, the total elongations were greater than 10%, which is a requirement for sheet steels for cold-formed framing members, such as ASTM A1003 ST340H, for application in residential and commercial construction. The Nb microalloyed UCS products, at all strength levels, passed a flat 180° bend test and exhibited excellent hole expansion performance.

**Age hardening heat treatments**. As noted earlier, TEM examination did not reveal any Nb precipitation in the hot rolled condition. This suggested that Nb was held in solid solution and potentially available for age hardening in 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 continuous annealing section of a conventional hot dip galvanising line for a range of peak temperatures and times. As an example, the response of the 0.084% Nb UCS steel to heat treatment is given in Fig. 3 (a) and outcomes are summarised below:

- Strengthening began at 625ºC, maximum strengthening occurred at 675 to 725ºC and over ageing at 750ºC.
- Maximum strength increment was about 150 MPa, producing yield strengths over 600 MPa.
- Strengthening response was not overly sensitive to time at temperature.

TEM examinations of over aged samples (750ºC), revealed very fine (4-15 nm) Nb rich precipitates, indicating strengthening via age hardening by Nb. Fig. 3 (b) summarises the laboratory age hardening evaluation, where the maximum strength increment is presented as a function of the Nb content of the steel. The results showed a progressive increase in age hardening strengthening increment with increasing Nb level.

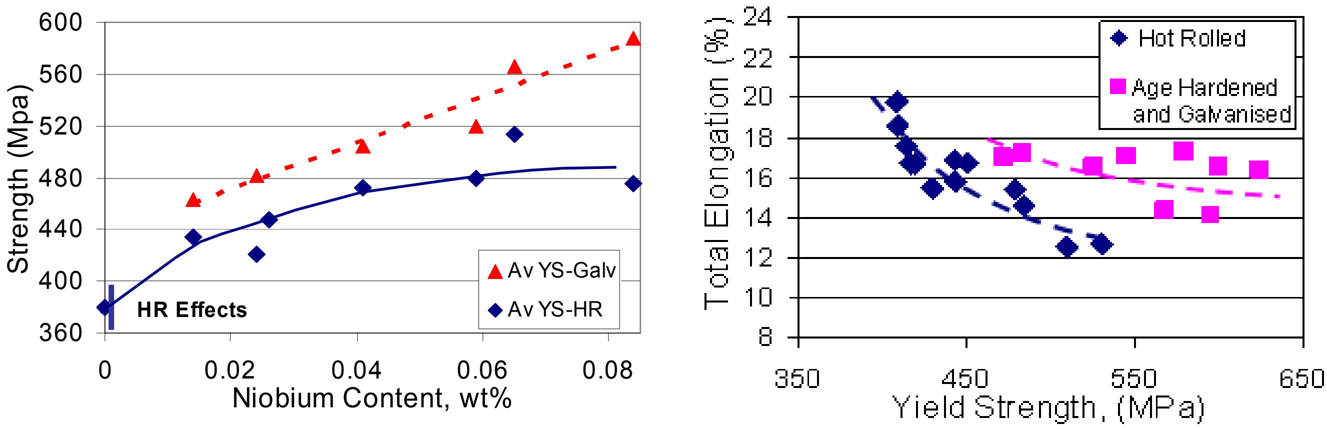
The response of Nb UCS steels observed in the short time heat treatments indicated the potential for age hardening these steels using a continuous annealing line or the annealing section of a hot dip continuous galvanising line. Subsequent full scale plant trials were conducted on a conventional hot dip galvanising line to age harden the Nb UCS steels and results are summarised in Fig. 4 (a) for UCS steels with different Nb additions. Significant and consistent strengthening was observed and the final strength levels were similar to that from the laboratory heat treatments. Final strength levels of over 450 MPa were recorded with 0.024% Nb and over 550 MPa with 0.08% Nb UCS steel. This outcome indicates the potential to further expand the range of UCS products to higher strengths and significantly increase the strength-thickness combinations possible for hot rolled structural strip grades.




a) b)

Fig. 3 a) Laboratory age hardening of 0.084% Nb UCS steel and b) Strength increase between the hot rolled and maximum age hardened strengths as a function of Nb level [3]

The total elongation results for the age hardened and galvanised Nb UCS products are presented in Fig. 4 (b) and compared to the results for the as-hot rolled Nb UCS steels. The results highlight that instead of a reduction in total elongation accompanying the strength increase from age hardening, the total elongations were actually either similar or higher in the age hardened and galvanised condition. This outcome provides an attractive combination of high strength and excellent ductility in thin strip. The microstructural changes that have produced this outcome are still under investigation.




a) b)

Fig. 4 a) Age hardening response of Nb UCS steels as a function of Nb content, b) Comparison of total elongation results between hot rolled and age hardened and galvanised Nb microalloyed UCS steels

## Conclusions

A wide range of Nb microalloyed, low C steels have been successfully strip cast by the CASTRIP® process and rolled to final strip thicknesses of 1.0 to 1.5mm. Niobium provided substantial microstructural hardening in the as hot rolled condition, through enhancing the hardenability. Niobium was also retained in solid solution enabling further significant strengthening to be achieved from an age hardening heat treatment. Strength levels ranging from 400 MPa to in excess of 550 MPa, in combination with high ductility, were achieved in the age hardened and hot dip galvanised condition, utilising a conventional hot dip galvanising line, substantially broadening the product range available in thin galvanised hot rolled strip.

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