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THE EFFECT OF NIOBIUM ADDITIONS ON FERRITE FORMATION IN CASTRIP® STEEL

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ABSTRACT

The relationship between niobium concentration, microstructure and mechanical properties has been studied in a production grade and microalloyed low carbon, Mn-Si Ultra-Thin Cast Strip (UCS) steels, produced by the CASTRIP®* process. An increase in niobium concentration corresponds to a ferrite grain refinement and an increase in yield strength of over 30%. Increases in yield strength have commonly been associated with either grain refinement, solid solution or precipitate strengthening, however transmission electron microscopy (TEM) of these UCS steels provide no clear evidence of Nb-based precipitate formation. It is therefore thought that strength enhancements are primarily a result of grain refinement, where this occurs due to the enhanced hardenability of the Nb bearing steel, where the addition of Nb results in a lower transformation temperature, leading to a much finer and more acicular ferrite morphology.

1. INTRODUCTION

Strengthening mechanisms including work hardening, solid solution strengthening, grain refinement and precipitate strengthening have been studied extensively over the past century in an effort to continuously improve the properties of steels. Increased demand for applications from construction, automotive, pipeline and pressure-vessel industries has accentuated the need for materials with a combination of strength and toughness. The influence of grain refinement has been designated as the key criterion for producing a good combination of mechanical properties according to the Hall-Petch effect.[1,2] This relates the yield stress (σ_y) to the grain diameter (d) according to

$$\sigma_y = \sigma_0 + kd^{-\frac{1}{2}} \qquad (1)$$

where σ_0 and k are constants. Typically varying production processes including rolling temperature, time and roll reduction can induce grain refinement, however compositional variations may also influence the grain size. The latter effect is observed in high-strength low-alloy (HSLA) steels, in which significant strength enhancements are observed due to grain size refinement.

In conventional steel castings containing the microalloying additions of Nb, V and Ti, carbonitride precipitates are commonly observed. These precipitates have been associated with grain refinement due to pinning of the austenite boundaries representing a pathway to increase strength. Precipitates are also possible nucleation sites for acicular ferrite, whose interlocking nature and ability to pin dislocations is thought to be responsible for significant improvements in the strength of a steel.[7-9] Much work has been carried out on the effect of austenite recrystallization and its influence on grain size. Researchers have shown that by retarding the recrystallization of austenite, either by solute drag or strain-induced precipitation,[3-6] the austenite grain boundaries per unit volume are maximised providing preferential nucleation sites and therefore optimal ferrite refinement. While many investigators have looked into the effect of thermomechanical treatments on grain refinement and mechanical properties, information on the role of composition is less widely available.

The CASTRIP® process is a revolutionary new twin-rolling technique for manufacturing strip cast steels, which compared to traditional casting requires less energy, time and space, while maintaining an increased output. Presently, only a base low-carbon steel grade is manufactured commercially using this process, however the influence of microalloying additions is being explored. A significant variation between conventional casting and the CASTRIP process is the rate of solidification. While conventional casting has a solidification rate in the time regime of minutes, UCS produced using the CASTRIP process are completely solidified within a fraction of a second. This variation is thought to have significant implications on the resultant microstructure.
* CASTRIP® is the registered trade mark of Castrip LLC.

Table 1. Chemical composition of the steel used in the investigation (wt.%).

Steel	C	Mn	Si	Nb	Ni	Cr	P	Cu	Mo	Al	Ti	N
Low-C Nb free	0.034	0.98	0.2	0.001	0.028	0.04	0.011	0.056	0.008	0.006	<0.002	0.0081
Low Nb	0.038	0.87	0.24	0.026	0.021	0.034	0.007	0.054	0.01	0.002	<0.003	0.0051
High Nb	0.037	0.93	0.28	0.065	0.028	0.042	0.009	0.063	0.008	<0.003	<0.002	0.007

2. MATERIALS AND METHODS

Ultra-thin cast strip (UCS) coils of a low-carbon manganese-silicon steel and two additional variations of Nb microalloyed steels were produced using the CASTRIP process, as has been described in detail elsewhere.[10,11] Three samples were compared. One sample was a production grade steel that did not contain the microalloying addition, Nb. The two other samples contained 0.026 and 0.065%Nb, respectively. Details of the chemical composition of these steels are given in Table 1. The yield strength was determined using uniaxial tensile tests and acquiring stress-strain curves for each sample. The yield strengths were 386 MPa, 424 MPa and 503 MPa, respectively.

Samples of the steel approximately 1 cm^2 were embedded in an epoxy resin at room temperature and then mechanically polished with silicon carbide abrasive paper down to a grit size of 1200. A colloidal suspension down to 1 μm grit was used for fine polishing to minimise scratches across the surface. To observe grain size and morphology, a 2% nital etch was applied for approximately 30 seconds. The metallographic information was acquired using an Olympus BX61 refected light microscope.

The microstructure of these samples was analysed using a JEOL 3000F TEM operating at 300kV. The specimens were prepared using a mechanical polishing method, and then thinned to electron transparency using the “H-bar” technique in a FEI Quanta 200 focused ion beam (FIB).

3. RESULTS

The microstructures of samples that had undergone ~35% inline hot rolling reduction, at a rolling temperature of between 880-950°C and a coiling temperature between 500-620°C were compared using light optical microscopy. The microstructure of the Nb free steel is provided in Figure 1 and consists of ferrite grains in a predominantly blocky morphology though both polygonal equiaxed and occasional acicular morphologies were observed. The grain sizes ranged between approximately 20-50 μm.

Very fine islands of pearlite were also observed uniformly throughout the microstructure. These are seen as dark regions in Figure 1 where the details of the pearlite structure remain unresolved under these imaging conditions.

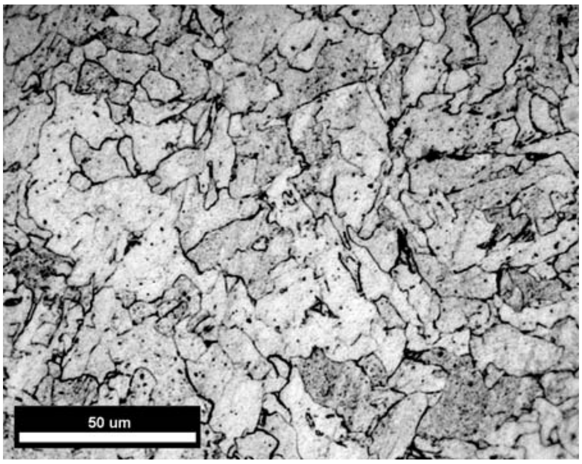

Figure 1. Light optical micrograph of low C Mn-Si UCS steel.

Typical examples of the microstructure of the Nb microalloyed UCS steels are provided in Figures 2 and 3 (0.026% and 0.065% Nb respectively). It is clear that the addition of Nb has resulted in a finer and more acicular ferrite microstructure. These microstructures consist of a variety of fine scale ferrite products including irregular blocky grain morphologies, Widmanstätten laths and, predominantly, acicular ferrite. Some unresolved pearlite was observed in the 0.026%Nb steel, Figure 2. The ferrite morphologies in these Nb containing steels is particularly interesting because there exists more curvature in the acicular laths than that usually associated with acicular ferrite.

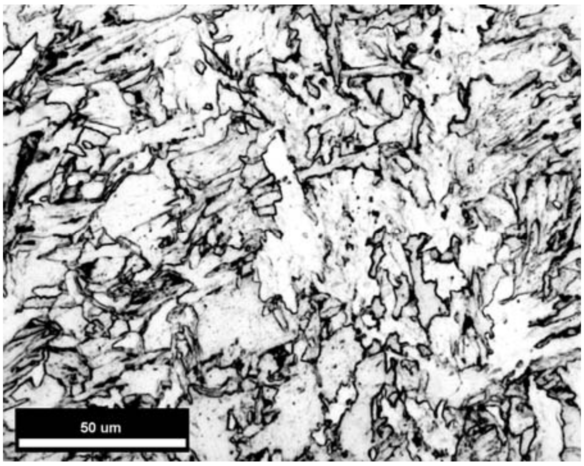

Figure 2. Light optical micrograph of microalloyed UCS steel with 0.026% Nb.

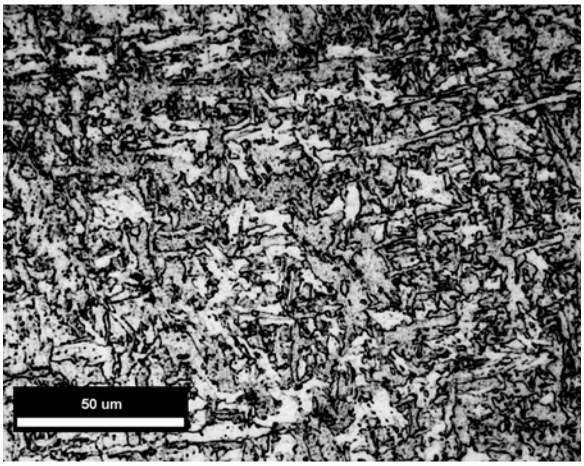

Figure 3. Light optical micrograph of microalloyed UCS steel with 0.065% Nb.

Figure 4 is a bright field-dark field pair of TEM images. Several ferrite grains are included in the field of view each at a unique orientation and diffraction condition. Fine scale speckled contrast is visible in some grains. Systematic tilting experiments were undertaken in order to carefully observe changes in contrast in these regions. These initial experiments lead us to conclude that this contrast is not from discrete second phase precipitates, but rather it originates from point defects and dislocations within the ferrite. Further work is in progress.

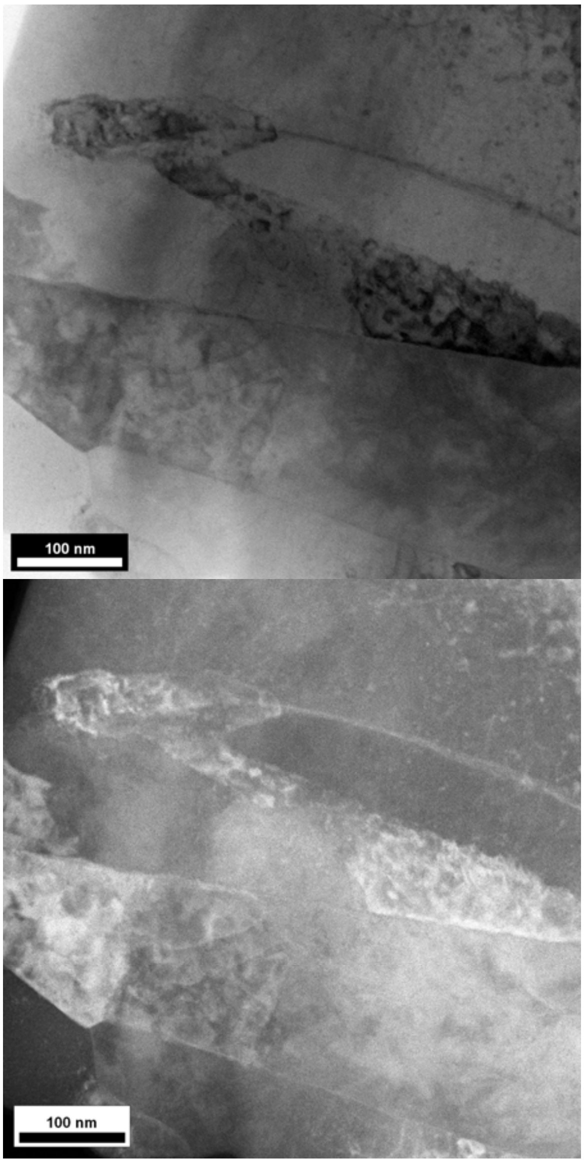

Figure 4. Bright field-dark field TEM micrograph of microalloyed UCS steel with 0.026% Nb.

4. DISCUSSION

For decades it has been known that niobium additions strengthen steels, however the exact nature of this strengthening mechanism is a complex mix of different factors. The influence of niobium on strength has been associated with 1) its ability to retard the recrystallization of austenite during deformation, 2) solid solution strengthening and 3) precipitate strengthening of the ferrite.[3,5,6] The relative influence of each is still not fully understood, and many models have been developed to account for different deformation variables including strain, temperature and grain size, in addition to the effect of strain-induced precipitation.[12-14] Early work by Kwon and DeArdo[5] suggested that NbCN particles nucleated in localised areas, most commonly along prior austenite grain boundaries and deformation bands. Due to the increased dislocation density in these regions they are expected to be preferred nucleation sites for precipitation. It is suggested that these localised precipitates were responsible for retarding the recrystallization of austenite and resulting in ferrite grain refinement, however no NbCN precipitates are observed in our steels and a refinement of ferrite still occurs. Pereloma et al.[6] also observed the formation of NbC precipitates at grain and sub-grain boundaries, however due to their rapid coarsening, these precipitates were not thought to influence the recrystallization process.

In the CASTRIP process where segregation and diffusion is limited, precipitate nucleation was minimal and the majority of the elements appear to stay in solution. It is particularly significant that high Nb levels can be trapped in solid solution as this has ultimately resulted in refinement of the ferrite microstructure and an increasing tendency for acicular morphologies. We propose that this is consistent with Nb increasing the hardenability of the steel and effectively decreasing the austenite-ferrite transformation temperature. The higher driving force for nucleation and the reduced mobility of solute result in significant refinement.

5. CONCLUSIONS

A strong correlation between the addition of increasing quantities of Nb and the morphology of ferrite in the microstructure was observed for low C Mn-Si UCS steels produced by the CASTRIP process. On a finer scale, no evidence of Nb-based precipitates were observed in these steels using TEM, as would be expected in conventional slab cast microalloyed grades. It is thought that the dramatically higher cooling rates in UCS steels suppress the formation of Nb-containing precipitates. Instead the strength enhancements are thought to be the result of an increase in the steels hardenability arising from a significant reduction in the transformation temperature. As a result, the predominantly blocky ferrite morphology of the Nb-free steel is replaced by a significantly finer acicular ferrite.

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