Acta Materialia 115 (2016) 167–177

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

# Effect of coiling treatment on microstructural development and precipitate strengthening of a strip cast steel

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## ARTICLE INFO

*Article history:*
Received 26 February 2016
Received in revised form
25 May 2016
Accepted 27 May 2016
Available online 9 June 2016

*Keywords:*
Strip casting
Precipitation
Atom probe tomography
Small angle scattering

## ABSTRACT

The effect of a simulated coiling treatment on a strip cast Nb-containing steel has been investigated. A lath ferritic supersaturated microstructure was observed in the as-cast condition with no coiling. The microstructure remained lath like during coiling at high temperature (850 °C) and the formation of chemically complex Nb-rich precipitates containing C, N, Si and S was observed. Coiling at an intermediate temperature (700 °C) caused the formation of polygonal ferrite with a dendritic morphology due to chemical micro-segregation. The polygonal ferrite contained Nb(C,N) precipitates. The microstructure remained lath like at the lowest coiling temperature (600 °C). In the latter case the precipitation of Nb-rich clusters was observed, and atom probe tomography revealed them to be ~85% Fe. Small angle neutron scattering and transmission electron microscopy were used to quantify precipitation kinetics during coiling and the mechanical properties were evaluated with a shear punch apparatus. A yield strength model was developed to describe the observed mechanical behaviour, and this showed that the two largest contributors to strength were the bainitic microstructure and the Nb-rich precipitates. Strategies to further strengthen these materials are suggested.

## 1. Introduction

Direct strip casting is a commercially viable steel sheet production process in which the liquid steel is solidified directly into thin sheet [1,2]. The process is typified by rapid solidification and non-equilibrium microstructural development. These fast cooling rates result in the as-cast structures of low carbon steels being a mixture of fine Widmanstätten ferrite, bainite, and martensite [3–9]. These lath-like structures result in high strength but low ductility and are hence not favourable for advanced engineering applications. However, industrial practice is not to cool the steel sheet directly to room temperature. Instead, the steel sheet is wrapped into a large coil, and the coiling temperature is known to be a critical parameter in the microstructural development of conventionally processed steel. For the case of direct strip cast steel, this variable is seldom studied. Reports have indicated that a well-designed coiling treatment can produce a dual phase microstructure consisting of polygonal ferrite and pearlite [3,5,6]. This has shown the potential of the coiling treatment to modify the sheet properties, but the kinetics of these microstructural changes have yet to be studied.

The formation of Nb precipitates during conventional processing of low alloy steels has been extensively studied in the literature [10–18]. These precipitates are generally found to contain Nb, C and N. Strip casting occurs too rapidly to allow precipitation of Nb(C,N), so in the as-cast condition the samples are essentially precipitate-free [9,19]. As a result, the precipitates are expected to form during the coiling process and it is thus important to optimise the coiling temperature and duration. The effect of interrupting the rapid cooling rate with a simulated coiling treatment on the microstructural development and precipitation process is unknown. Low C low Nb steel samples were prepared using a dip tester to simulate the direct strip casting process. Coiling was performed at 3 temperatures to simulate coiling in the austenite (850 °C), during the austenite decomposition (700 °C) and in the ferrite (600 °C).

One of the most challenging aspects of studying the strip cast microstructure is the inhomogeneity of the microstructure across the nano- and micro-length scale [3,9,18–22]. Thus to provide statistically robust measurements we augment standard electron

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http://dx.doi.org/10.1016/j.actamat.2016.05.043
1359-6454/

microscopy and atom probe tomography studies with small angle neutron scattering experiments. The mechanical properties of the coiled samples were investigated using a shear punch test apparatus. The combination of these local-scale and macroscopic measurement techniques provides a full description of the microstructures, allowing correlation between microstructure and mechanical properties. A yield strength model is used to understand the different contributions to strengthening and strategies to further strengthen these materials are suggested.

## 2. Materials and experimental methods

The composition of the material investigated is detailed in Table 1. The continuous cooling temperature diagram for this alloy was recently established in conditions pertinent to strip casting [9], Fig. 1. Coiling times and temperatures were selected to correspond to (1) coiling in the austenite (850 °C), (2) coiling during the austenite decomposition (700 °C) and (3) coiling after complete transformation to ferrite (600 °C).

The direct strip casting process was simulated using a lab-scale simulator know as a dip tester. The dip tester apparatus is described in detail elsewhere [23]. With this apparatus, a copper substrate is immersed into the liquid steel and rapidly extracted. In order to simulate the coiling treatment, the samples were then manually transferred into a muffle furnace pre-heated to the coiling temperature. After coiling, the samples were removed from the muffle furnace and air cooled.

Samples were sectioned and metallographically prepared using the usual methods. The final polishing step used was at least 5 min of polishing using colloidal silica. For optical microscopy, samples were etched in a solution of 5% nitric acid in ethanol, but no etching was required for scanning electron microscopy. Scanning electron microscopy (SEM) was carried out on a Jeol JSM 7800F equipped with a field emission electron gun.

**Table 1**
Composition of the steel tested in the present study in wt%.

| C | Nb | Mn | Si | S | P | N | Fe |
|---|---|---|---|---|---|---|---|
| 0.11 | 0.16 | 0.59 | 0.16 | 0.0006 | 0.009 | 0.008 | bal |

Samples for transmission electron microscopy (TEM) were prepared by electro-polishing in a solution of 5% perchloric acid in acetic acid. TEM observations were made on a JEOL 2100F TEM equipped with a field electron gun, energy dispersive spectroscopy (EDS) and a Gatan electron energy loss system (EELS).

Atom probe tomography (APT) was carried out on a LEAP 4000 HR instrument at a pulse fraction of 200 kHz, a temperature of 60 K, and pulse fraction of 20%. Samples were prepared by electro-polishing in a micro-loop apparatus under an optical microscope in a solution of 5% nitric acid in ethanol at room temperature [24,25]. Electro-polished tips were given a final sharpen using Ga ions at 10 kV in Quanta dual beam FIB.

The SANS experiments were carried out at the Australian Nuclear Science and Technology Organisation (ANSTO) on the Quokka beamline [26]. The samples were mechanically polished down to a thickness of 300 μm. An electromagnet was used to apply a 1 T magnetic field perpendicular to the neutron beam in order to magnetically saturate the Fe-Matrix [19]. The samples were exposed to the neutron beam for 30 min. A sample-to-detector distance of 4 m was used, to cover a q-range of 0.015–0.15 $\text{Å}^{-1}$.

Shear punch tests were performed on a locally designed apparatus [27]. The shear punch load was converted into an equivalent tensile stress $\sigma_y$ following [27]:

$$\sigma_y = \sqrt{3}\ \frac{F}{2 \times \pi \times t \times r} \tag{1}$$

where F is the load on the punch, t is the thickness of the specimen and $r = (r_p + r_d)/2$ with $r_p$, the radius of the punch and $r_d$, the radius of the die. In the present case r = 0.1 mm.

Nano-hardness experiments were performed with an Ultra Micro Indentation System (UMIS). A constant load of 3 mN was used during the tests.

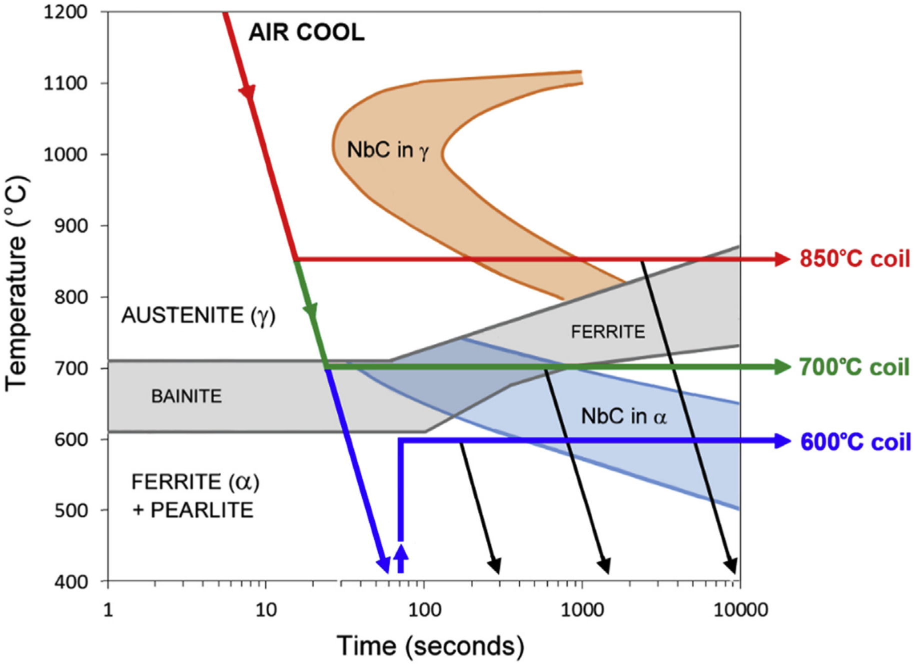

**Fig. 1.** Mixed CCT/TTT diagram of the studied alloy, taken from Ref. [9]. The coiling temperatures selected for this study are highlighted.