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The effect of cooling rate and coiling temperature on the niobium retention in Ultra-Thin Cast Strip steel

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ABSTRACT

This laboratory study utilised a dilatometer to simulate the run-out table cooling rate and the coiling temperature to investigate the effect of the cooling rate and simulated coiling conditions on the age hardening response of a niobium microalloyed Ultra-thin Cast Strip (UCS®) steel, produced by the CASTRIP® Process. Three cooling rates of 1, 5 and 40 °C/s, covering very slow (1 °C/s) to typical run-out table cooling rates (40 °C/s), down to two coiling temperatures of 500 and 675 °C were used. Dilatation curves were used to determine the temperature range over which the γ-α phase transformations occurred and the final microstructures were characterized using an optical microscope equipped with an image analysis software. The subsequent age hardening response, which previous studies have shown, results from the retention of Nb in solid solution, was assessed by the hardness changes after a post heat treatment at 700 °C for 60 s. A range of age hardening responses were obtained, depending on cooling rates and cooling stop (coiling) temperatures, which indicate a different degree of Nb retention. At the same cooling rate, the lower coiling temperature of 500 °C resulted in higher Nb retention compared to the higher coiling temperature of 675 °C. As the coiling temperature of 675 °C was within the austenite to ferrite transformation range, the simulated slow cooling of the coil impacted the precipitation behaviour of Nb rendering the interpretation more complex and this will be discussed in this paper. For the 500 °C simulated coiling temperature, the higher cooling rate resulted in a higher age hardening increment thus more Nb retention.

1. Introduction

CASTRIP® process is a revolutionary strip casting technique for producing Ultra-Thin Cast Strip steel, which has many advantages over conventional casting and rolling technologies, including a smaller carbon foot print, lower cost of production and simpler and more flexible operating conditions. The world's first commercial installation of the CASTRIP process for the production of Ultra-Thin Cast Strip (UCS) is located in Nucor Steel's Crawfordsville, Indiana plant. The facility has been producing low-carbon sheet steel since its start-up in 2002 [1]. The CASTRIP process is mainly composed of three parts: twin-roll casting, hot rolling reduction, controlled cooling process. The strip is produced from liquid steel with a rapid solidification rate by twin-roll casting, followed by hot rolling reduction to final thicknesses of 0.9–1.5 mm. Finally, on the run-out-table, the steel is controlled cooled by air-mist water cooling. The control of the cooling rate and the stop cooling temperature on the run-out-table plays an important role in achieving the desired microstructure and mechanical properties of the UCS products.

There are several strengthening mechanisms operating in Nb microalloyed UCS steel [2–5], including microstructural hardening, and solid solution hardening. In addition, due to the retention of Nb in solid solution [2], age hardening, through the precipitation of Nb rich particles, can be utilised to further strengthen Nb microalloyed UCS steel by post-processing operations, such as during continuous hot dip galvanising [3]. It is well known that the effective precipitation hardening performance can be achieved by a post heat treatment if more Nb retained in solid solution after the CASTRIP process. In addition, it is important to note that the cooling rate and the coiling temperature on the run-out-table, not only can have a significant effect on the retention of Nb, but also on the microstructure and the mechanical properties of the strip. Therefore, in order to effectively control the mechanical properties of the CASTRIP product, it is necessary to study the influence of the cooling rate and coiling temperature on the Nb retention in UCS steel in CASTRIP process.

A considerable amount of research works, about the influence of

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Table 1
Chemical composition (wt%) of the UCS steel.

Element	C	P	Mn	Si	S	Ni	Cr	Mo	Cu	Nb	N
	0.031	0.014	0.738	0.159	0.003	0.047	0.057	0.017	0.095	0.059	0.005

cooling conditions on precipitation hardening, focused on diffusion time and diffusion rate of solute atom during continuous cooling process [6]. While only a small number of studies focused on major precipitation region in which the solute atoms precipitate out during cooling control process [7]. Therefore, the aim of the present study was to further investigate the potential effect of the cooling rate and coiling temperature on the retention of Nb in solid solution during the controlled cooling process over a wider range of processing conditions than can practically be achieved under industrial run-out table cooling conditions, viewed from phase transformation temperature range where the NbC precipitates are mainly produced. To undertake this study, the age hardening response, as measure by the change in hardness, was utilised to reflect the retention of Nb in solid solution in Nb microalloyed UCS steel.

2. Experimental procedure

UCS steel strip produced by the CASTRIP process used in the present study was supplied by BlueScope Steel, Port Kembla, and the chemical composition is listed in Table 1.

The thickness of the strip was 1 mm, so it was too thin to make standard sized dilatometry samples. An alternative sample design, rectangular shape with an arm on each end, was used in this investigation, as shown in Fig. 1. The heat treatment experiments were carried out on a Theta Industries-Dialatronic dilatometer.

The dilatometry experimental program is schematically shown in Fig. 2. The experimental conditions are aimed to simulate the thermal path of the Castrip processing though they do not include a hot deformation step to simulate the hot rolling process. The absence of a hot deformation component was not considered significant to the aims of this study, given the low hot rolling reductions usually applied and the short time period after hot rolling, before cooling is applied, that restricts strain induced precipitation occurring. The samples were heated to the solution temperature of 1280 °C at 20 °C/s and held for 5 min under vacuum to simulate the coarse austenite grain size in as-cast UCS. Specimens were then cooled to 900 °C at 50 °C/s, to simulate the relatively rapid cooling of thin strip between casting and hot rolling. After a 60 s dwell period at 900 °C, the samples were cooled to the coiling temperature of either 500 or 675 °C, at three different cooling rates of 1, 5 or 40 °C/s, respectively. To simulate the slow cooling of a coil, the samples were cooled to 300 °C at the cooling rate of 0.17 °C/s from the coiling temperatures, before helium gas quenching to room temperature.

The heat treated samples were divided into two parts by using an Accutom 5/50 sectioning machine. One part was used for the microstructure characterisation and hardness measurements, while the other part was utilised for the post-processing age hardening treatment, which was carried out in the dilatometer. These samples were aged at 700 °C for 60 s and cooled to room temperature by helium gas quenching, as shown schematically in Fig. 3, then the hardness was measured.

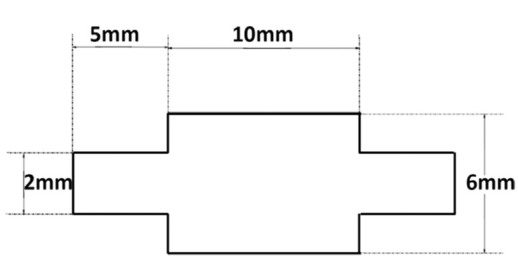

Fig. 1. The geometry of the dilatometery samples.

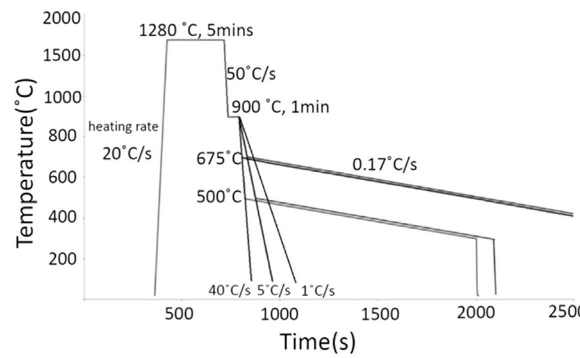

Fig. 2. Schematic illustration of the Heat treatment simulation for the CASTRIP process.

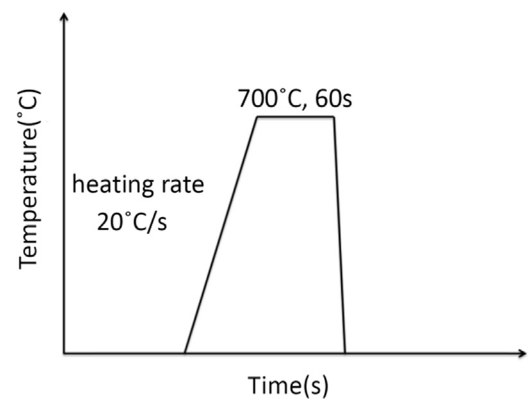

Fig. 3. Schematic of simulated post age hardening heat treatment.

Optical metallography was carried out on a LEICA DMR optical microscope. The samples were hot mounted on a Struers CitoPress-20 mounting machine, then grinded and polished to a 1 µm finish using a Struers grinding and polishing machine and etched in 2% Nital.

Vickers hardness and micro Vickers hardness tests were performed on an INDENTEC Vickers hardness testing machine with a load of 1 kg and LECO M-400-H1 micro Vickers hardness testing machine with a load of 50 g, respectively. The Vickers hardness of the samples or micro Vickers hardness of each microstructure constituent was measured as an average of eight tests.

The dilatation curve shown in Fig. 4 was obtained by combining the dilatometer data and the microstructure observations of the steel. Microsoft Excel was used to assist in drawing the dilatation curve.

Due to the difficulty in revealing the prior austenite grain boundaries of low carbon UCS steel by using picric acid, the austenite grain boundaries were delineated using ferrite, as shown in Fig. 5. The austenite grain size was then measured using the linear intercept method.

The volume fraction of each constituent of the samples was estimated by using the imaging analysis software Axiovision and Microsoft Excel. There are a number of nomenclature systems for describing the range of ‘lower transformation ferritic products’ that form in steel [8–12]. In this paper, the ISIJ transformation products nomenclature [8] was adopted because it is well suited for low carbon steels [4,8]. The typical order of ferritic transformation products are: Polygonal Ferrite (PF), Quasi-Polygonal Ferrite (QPF), Widmanstätten Ferrite