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The determining impact of coiling temperature on the microstructure and mechanical properties of a titanium-niobium ultrahigh strength microalloyed steel: Competing effects of precipitation and bainite

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ABSTRACT

We elucidate here the influence of coiling temperature on the microstructure and mechanical properties, in an ultrahigh strength titanium-niobium microalloyed steel. The objective was to underscore the impact of coiling temperature on the nature and distribution of microstructural constituents (including different phases, precipitates, and dislocation structure) that significantly contributed to differences in the yield and tensile strength of these steels. Depending on the coiling temperature, the microstructure consisted of either a combination of fine lath-type bainite and polygonal ferrite or polygonal ferrite together with the precipitation of microalloyed carbides of size ~2–10 nm in the matrix and at dislocations. The microstructure of steel coiled at lower temperature predominantly consisted of bainitic ferrite with lower yield strength compared to the steel coiled at higher temperature, and the yield to tensile strength ratio was 0.76. The steel coiled at higher temperature consisted of polygonal ferrite and extensive precipitation of carbides and was characterized by higher yield strength and with yield strength/tensile strength ratio of 0.936. The difference in the tensile strength was insignificant for the two coiling temperatures. The observed microstructure was consistent with the continuous cooling transformation diagram.

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1. Introduction

There is currently a strong demand for ultrahigh strength steels for a wide range of structural applications, including pipes for downhole applications [1,2]. Ultrahigh strength (yield strength of greater than ~700 MPa) is an important requirement. Traditional thermo-mechanical controlled processing (TMCP) is commonly employed to refine the microstructure together with the optimization of processing parameters such as finishing and coiling temperature to obtain desired mechanical properties [2,3]. Microalloyed structural steels with minimum yield strength of 350 and 460 MPa have been successfully developed [4,5]. In recent years, quenched and tempered (QT) [6,7], quenched, lamellarized and tempered (QLT) [8], transformation-induced plasticity (TRIP) [9], and quenched and partitioned (Q&P) [10,11] heat treatments are also being developed to obtain high strength in steels. In thermo-mechanically processed hot rolled steel strips, the microstructure and mechanical properties are significantly influenced by the process parameters, such as rolling ratio, rolling temperature, cooling pattern, cooling rate and the coiling temperature. Among them, the influence of coiling temperature is considered to be significant [1,12]. Undoubtedly, controlling the coiling temperature is the most economical and efficient way to improve the properties of microalloyed steels. Furthermore, the coiling temperature governs the precipitation of microalloying elements, such as Nb, V, Ti and Cu [13–16], which are expected to play a strengthening role via nano-scale precipitation. In Nb-Ti microalloyed steels, the precipitation of Nb and Ti is particularly sensitive to the coiling temperature [17–21]. However, studies related to the optimization of mechanical properties through the control of coiling temperature in microalloyed steels are relatively uncommon. In the present study, a low carbon Nb-Ti microalloyed steel was hot rolled and coiled at two different temperatures. The mechanical properties, namely, yield strength and tensile strength were related to the microstructure to elucidate the effect of coiling

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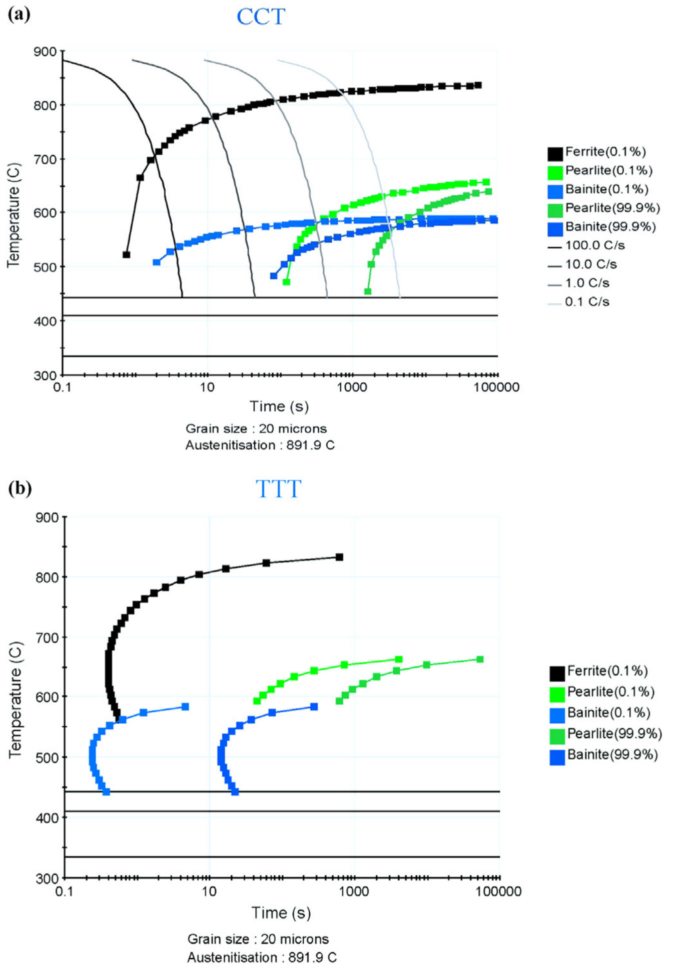

Fig. 1. (a) Continuous cooling transformation diagram and (b) temperature-time-transformation diagram.

temperature. Toughness was not an aspect of concern given that the steel was processed for linepipes for downhole applications. Only elongation is of relevance. The findings from the present study are expected to provide a fundamental basis for the development of high strength hot-rolled steels where yield strength and tensile strength are important requirements.

2. Experimental procedure

The chemical composition of the studied steel in wt% was in the range of (0.03–0.07)C, (1.5–2.0)Mn, (0.2–0.4)Si, (0.5–0.7)(Cr+Nb+Ti), 0.003S, 0.004N, 0.03Al, 0.002Ca and balance Fe, where Nb and Ti were added for precipitation strengthening and grain refinement, and Mo was added to enhance hardenability and promote bainite formation. The microalloyed steel discussed here were industrial heats that were continuously cast and hot rolled to the desired thickness. Two coiling temperatures were studied, namely 520 °C and 600 °C.

Standard tensile tests were conducted at room temperature on longitudinal specimens machined according to ASTM E8 specification (dimensions 225 mm × 12.5 mm, gauge length 50 mm) using computerized tensile test system.

Transmission electron microscopy was carried out on thin foils prepared by cutting thin wafers from the steel samples, and grinding to ~40 μm in thickness. Three millimeter discs were punched from the wafers and electropolished using a solution of 10% perchloric acid in ethanol. Electron transparent foils were examined by Hitachi H9500 TEM operated at 200 kV.

3. Results and discussion

3.1. *The CCT and TTT diagrams*

The CCT and TTT diagrams of the studied steel, as calculated by JMatPro are presented in Fig. 1. JMatPro assumes grain size of 20 μm after austenitization at 900 °C. It can be seen that the bainite start temperature (Bs) and martensite Ms are 600 °C and 450 °C, respectively. Fig. 1 predicts that coiling at 600 °C and 520 °C, the corresponding transformation products are ferrite (or ferrite-pearlite) depending on the cooling rate and bainite, respectively.

3.2. *Mechanical properties*

Yield strength, tensile strength, yield strength/tensile strength ratio of steels coiled at two different temperatures is presented in Table 1. Coiling at 520 °C, the average yield strength was ~633 MPa (91.8 ksi) and tensile strength was ~831 MPa (120.5 ksi). While coiling at 600 °C, yield strength and tensile strength were ~807 MPa (117 ksi) and ~862 MPa (125 ksi) respectively. The elongation was in the range of 13–15%. Thus, there is a distinct effect of coiling temperature, particularly, on yield strength, but differences in tensile strength were small. The significant difference in yield strength must be related to microstructural constituents.

3.3. *Fine-scale microstructure*

Representative scanning electron micrographs (SEM) and bright field transmission electron micrographs (TEM) illustrating the general microstructure of investigated steels are presented in Figs. 2–8. Steel coiled at 520 °C predominantly consisted of bainite with some polygonal ferrite, whereas steel coiled at 600 °C was largely characterized by polygonal ferrite (also see below Figs. 2–4). Based on CCT and TTT diagrams, nucleation of martensite is not a possibility. The TEM micrographs of lower coiling temperature steel was characterized by a dual-phase microstructure consisting of bainitic laths and polygonal ferrite (Figs. 3 and 4). The area fraction of polygonal ferrite and bainite estimated from a number of micrographs was ~20–25% and ~75–80%, respectively. However, higher coiling temperature steel primarily consisted of polygonal ferrite (Fig. 3). The polygonal ferrite grains were in the size range of ~1–2 μm containing a high density of dislocations. The width of bainite laths was in the size range of ~0.5–1.0 μm.

Table 1
Average tensile properties for samples coiled at 520 °C and 600 °C.

Coiling temperature: 520 °C				**Coiling temperature: 600 °C**			
Yield strength (MPa)	Tensile strength (MPa)	Yield ratio (YS/TS)	% Elongation	Yield strength (MPa)	Tensile strength (MPa)	Yield ratio (YS/TS)	% Elongation
633	831	0.76	13–15	807	862	0.94	13–15

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