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Microstructure, precipitation and mechanical properties of a titanium-tungsten alloyed hot rolled high strength steel

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ABSTRACT

A new titanium-tungsten-bearing hot rolled high strength bainitic steel was developed through the design of chemical composition and rolling processing. The chemical composition of 0.04C-0.1Ti-0.4W (wt%) was determined to make full use of alloying elements through considering the atomic ratio of elements. The rolling condition in the region through austenite recrystallization to austenite non-recrystallization region was adopted to realize a homogenous and fine microstructure. The effects of coiling temperature (CT) on the microstructure, precipitation and mechanical properties of the steel were investigated. Results showed that the average effective grain sizes of bainite ferrite were measured to be 2.2 µm, 1.8 µm and 2.4 µm for the sample of CTs 550 °C, 600 °C and 650 °C, respectively. The precipitates formed during coiling process were identified as nanoscale NaCl-type (TiW)C carbides that contain a high level of Ti and W. As CT increases, the precipitation amount of nanoscale precipitate increases. At the CT of 600 °C, an optimal combination of strength and ductility was achieved (yield strength: 733 MPa; ultimate tensile strength: 806 MPa; uniform elongation: 14.9%; total elongation: 24.4%). In addition, due to re-precipitation of nanoscale carbides, the strength of the steels coiled at 600 °C was obviously increased after tempering at 650 °C for 15×10^3 s holding, exhibiting superior ageing strengthening effect.

1. Introduction

The mechanical properties of low carbon steels are significantly enhanced by adding a small amount of microalloying elements (e.g. Nb, V and Ti) into them. Such types of steel are so-called "microalloyed steels" [1]. Grain refinement and precipitation hardening are the two main factors that improve the strength of microalloyed steels [1–3]. In recent years, more and more attention is paid to steels with the titanium content of ≥ 0.1 wt%, so-called "high Ti-microalloyed steels", due to their lower production cost compared to Nb and V microalloyed ones [4–23]. Mao et al. [4,5] successfully developed a 700 MPa Grade Ti microalloyed strip steel via compact strip production (CSP) technology. The microstructure of the steel is composed of fine grain ferrite, pearlite or intergranular cementite and dispersive nanoscale TiC particles. The contribution of precipitation hardening to the yield strength from nanoscale TiC particles in this steel reaches 120 MPa. Later, Peng et al. [6] developed a Ti microalloyed plate steel through thermomechanical control process (TMCP) and found that a large number of nanoscale TiC precipitates were formed at the isothermal temperature of 600 °C, which results in a significant increase of strength. Based on Ti microalloyed steel, several complex microalloyed steels such as Ti-V [24], Ti-Nb [25] and Ti-Mo [13–16,18–22] were developed. Among them, a Ti-Mo microalloyed steel (composition: 0.04C-0.1Ti-0.2Mo in wt%) with a trade name of "Nanohiten" developed by JFE corporation has received much attention [13]. Compared to pure TiC in Ti steel, complex (TiMo)C carbide in Ti-Mo steel has superior coarsening resistance. Accordingly, the contribution from precipitation hardening to yield strength reaches up to ~ 300 MPa [13,14]. Moreover, the steel possesses an excellent uniform ductility with a ~ 120% hole expanding ratio and a good stability of mechanical properties after high temperature heat treatment [13,26].

Recently, a computational study by Jang et al. [14] showed that similar to (TiMo)C carbide in Nanohiten steel, a (TiW)C carbide in Ti-W steel also has a superior coarsening resistance, which make Ti-W steel have the potential of development and application. However, it is unknown whether the Ti-W steel can reach the same strength grade as Nanohiten, and the nanoscale (TiW)C carbides in terms of strengthening steel matrix still needs to be explored. Therefore, the aim of this paper is to develop a new Ti-W alloyed hot rolled steel through designing chemical composition and thermo-mechanical control process.

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The microstructure, precipitation and mechanical properties (as-rolled and as-tempered states) are investigated in details. An overall comparison in microstructure and mechanical properties between the present steel and Nanohiten will be made. Furthermore, the compositional evolution of (TiW)C carbides and strengthening mechanism of the developed steel were discussed in details.

2. Experimental procedure

2.1. Composition design

The typical chemical composition of Nanohiten steel developed by JFE is 0.04C-0.1Ti-0.2Mo (wt%) [13]. The design philosophy is to make C, Ti and Mo react to fully form (TiMo)C. Since the relative atomic mass of W (184) is almost twice of that (96) of Mo, the content of W is determined as 0.4% in the present study. Based on the above idea, the composition of the present steel is designed as 0.04C-0.1Ti-0.4W (wt%). Moreover, the content of Mn is designed as 1.5 wt% with the purpose of reducing the $\gamma \rightarrow \alpha$ phase transformation [3,13], which can refine the microstructure. The content of Si was designed as a regular amount with a value of 0.2 wt%. S and N are controlled as low as possible to decrease the formation of $Ti_4S_2C_2$ and TiN which have larger sizes of > 100 nm [7], and thus leave more Ti that can be precipitated during rolling process and coiling process.

2.2. TMCP schedule

The actual chemical composition of the steel studied was 0.043C-0.095Ti-0.39W-1.50Mn-0.2Si-0.0035S-0.0060P-.0022N (wt%). The steel was prepared by vacuum induction melting and hot forged to 26 mm thick bars. Fig. 1 shows the schematic illustration of TMCP schedule. Hot-forged bars were solution-treated at 1200 °C for 1 h and air-cooled to the starting rolling temperature of 1100 °C. The rolling process was composed of 7 passes with the total reduction of 92% at temperature ranging from 1100 °C to 900 °C, which goes through from austenite recrystallization to austenite non-recrystallization region. The finishing rolling temperature (FRT) is designed as 900 °C to achieve the best combination of mechanical properties [19]. After rolling, to simulate hot-coiling process, the specimens were laminar cooled at approximately 30 °C/s to 550 °C, 600 °C and 650 °C and held at that temperature for 1.0 h followed by furnace cooling to room temperature. In order to study the stability of mechanical properties of as-rolled strips, tempering heat treatment were conducted at 650 °C for long term holding (see Fig. 1).

2.3. Microstructure observation and precipitate characterization

The samples for optical microscopy analysis were prepared in an etchant of 4% nital after the standard mechanical polishing. Electron backscatter diffraction (EBSD) was employed to identify the effective grain size and its distribution, and the volume fraction of low angle boundary. A step size of 0.19 μm was used. The surface of the tested sample was first ground on conventional grinding papers and then electro-polished using 92% acetic acid + 8% perchloric acid at 60 V at room temperature for 15 s. The data measured was interpreted by orientation imaging microscopy analysis software.

The mass fractions of carbides were determined using physical-chemical phase analysis [1,2,22]. The phase structures of precipitates were identified by X-ray diffraction. The carbon extraction replica technique was used for the observation of the precipitates by means of high resolution transmission electron microscopy (HRTEM 2100 F). The particle sizes of the precipitates were measured by a software, Nano Measurer 1.2.5. In addition, the energy dispersive X-ray spectroscopy (EDS) was used to identify the composition of the precipitates during the TEM analysis.

2.4. Mechanical properties measurement

Tensile tests were performed using an Instron5500 machine at room temperature. The samples with their longitudinal axis aligned parallel to the rolling direction were machined in the gauge section of the tested sample 50 mm × 10 mm × 2 mm (length × width × thickness). The strain rate was set as 5×10^{-3}/s.

3. Results and discussion

3.1. Microstructure

Optical observation was performed for the samples coiled at different CTs, as shown in Fig. 2. It is seen that the microstructures of the experimental steels at different CTs were all composed of bainite (B) and a small amount of polygonal ferrite (PF). This is different from that of Nanohiten steel, in which ferrite is the dominant microstructure. As CTs increases, the microstructure becomes coarser slightly and the amount of PF increases. By the point counting method [3], the volume fraction of PF was measured to be 2% at 550 °C, 4% at 600 °C, and 15% at 650 °C.

The EBSD images showing the boundaries of the samples with different CTs are shown in Fig. 3, where the high ($\theta \geq 15^\circ$) and low ($2^\circ \leq \theta < 15^\circ$) misorientation angle boundary are indicated as black and red lines, respectively. At a glance, no significant difference was observed among the microstructures of the samples with different CTs. Thus, the orientation imaging microscopy analysis software was employed for quantifying the boundaries. Fig. 4 show the low angle boundary misorientation distribution ($2^\circ < \theta < 15^\circ$) and effective grain diameter distribution of the steels coiled at different temperatures. It reveals that the fraction of low angle boundaries for the samples 550 °C and 600 °C are similar. But it is relatively smaller for the sample 650 °C. These results indicate that the samples 550 °C and 600 °C have higher dislocation density than the sample 650 °C [3]. This matches well with the

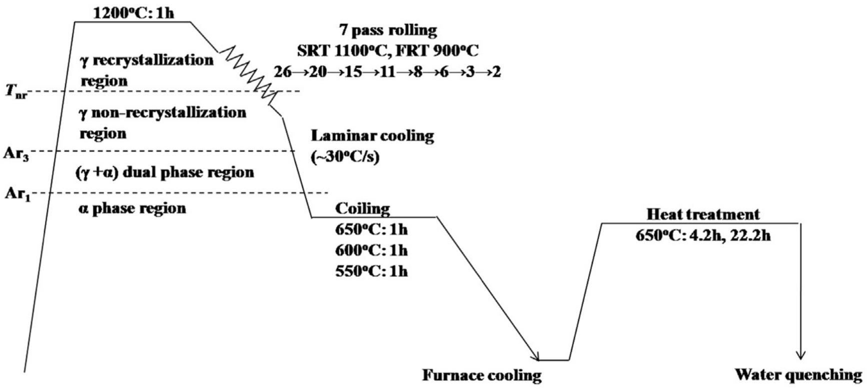

Fig. 1. Schematic illustration describing the TMCP schedule employed.