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Strengthening Mechanisms for Ti- and Nb-Ti-micro-alloyed High-strength Steels

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Abstract: The strengthening mechanisms of hot-rolled steels micro-alloyed with Ti (ST-TQ500) and Nb-Ti (NT-TQ500) were investigated by examining the microstructures of steels using optical microscope (OM), scanning electron microscope (SEM) and transmission electron microscope (TEM). The results revealed almost no differences in the solute solution strengthening and fine-grained strengthening of the two steels, whereas the contributions of precipitation strengthening and dislocation strengthening were different for ST-TQ500 and NT-TQ500. The measured precipitation strengthening effect of ST-TQ500 was 88 MPa higher than that of NT-TQ500; this difference was primarily attributed to the stronger precipitation effect of the Ti-containing nanoscale particles. The dislocation strengthening effect of ST-TQ500 was approximately 80 MPa lower than that of NT-TQ500. This is thought to be related to differences in deformation behavior during the finishing rolling stage; the inhibition of dynamic recrystallization from Nb in NT-TQ500 (Nb-Ti) may lead to higher density of dislocations in the microstructure.

Key words: micro-alloying; titanium; niobium; high-strength steel; strengthening mechanism

The strengthening of steel has become important in the automotive industry, construction machinery industry, and other industries because it can reduce the mass of equipment to save energy and reduce emissions[1-4]. Micro-alloying[1-4] is the addition of trace elements (such as Nb, Ti and V) to traditional C-Mn steels or low-alloy steels. In this manner, micro-alloyed elements combined with the thermal mechanical control process (TMCP) technology can control the precipitation behavior of micro-alloyed steels. For example, grain refinement and precipitation strengthening can be used to control the size, morphology, and distribution of carbide and nitride at different temperatures and to improve the strength of steel without loss of toughness or formability.

Previous studies have shown that the strengthening effect is obvious when two or more types of micro-alloyed elements (e.g., Nb-Ti and Nb-V) are added to steels[1-4]. At present, Nb-Ti-micro-alloyed steel is commonly used in construction machinery[5-8]. However, steel production costs are increasing significantly with the rising prices of ore and raw materials. Nb, V, and Ti are the three most commonly used micro-alloying elements. Among these three elements, Ti is the least commonly used; thus, the production of high-strength steels micro-alloyed with only Ti has recently attracted more attention from researchers and producers[5-8]. To date, high-strength steels micro-alloyed with Ti at levels of 450—650 MPa have been produced via compact strip production (CSP)[5-7]. However, there are lack of systematic studies on the Ti-micro-alloyed steels using traditional thick-slab production processes, particularly studies on the strengthening mechanisms of Ti-micro-alloyed high-strength steel. Consequently, this study focused on the strengthening mechanism of Ti-micro-alloyed high-strength steel produced by

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the traditional "thick slab + hot rolling" hot-strip process. The properties of Ti-micro-alloyed high-strength steel were compared with those of Nb-Ti-micro-alloyed high-strength steel.

1 Experimental

1.1 Chemical composition and production process

The yield strength level in the two experimental alloys was 500 MPa. The steel micro-alloyed with Ti only was labeled ST-TQ500, and the steel micro-alloyed with Nb-Ti was labeled NT-TQ500. The corresponding chemical compositions are listed in Table 1.

The production route was as follows: hot metal pretreatment→smelting→argon treatment→LF processing→continuous casting→heating→descaling→rough rolling→finish rolling→cooling→coiling. The plate thickness was set to 12 mm. Both ST-TQ500 and NT-TQ500 were processed by the following rolling parameters: finish rolling temperatures of 850—900 ℃ and coiling temperatures of 570—590 ℃.

Table 1 Chemical compositions of the ST-TQ500 and NT-TQ500 steels mass%

Material	C	Si	Mn	P	S	Nb	Ti	Al	N
ST-TQ500	0.071	0.07	1.68	0.01	0.005	0	0.08	0.04	0.0040
NT-TQ500	0.070	0.07	1.71	0.01	0.005	0.04	0.04	0.04	0.0045

1.2 Microstructure and mechanical testing

Tensile specimens were prepared with rectangular cross-section dimensions of 12.5 mm×56.5 mm and were tested at room temperature under a strain rate of 1×10^{-4} s^{-1}. Samples for toughness testing were machined into standard Charpy V-notch specimens with dimensions of 10 mm×10 mm×55 mm. The testing temperature was set as −20 ℃.

Microstructural observation was performed on the longitudinal sections of the samples taken from the tails of coils using optical microscopy (OM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The microstructures of samples cut from the 1/2 and 1/4 surfaces of the cast billet were also examined. Samples for TEM with diameters of 3 mm were prepared as follows: the samples were initially abraded to thicknesses of 40 μm; thin films were then prepared by electropolishing with a 5 vol.% perchloric acid-glacial acetic acid solution. TEM was performed using a JEM-2100 microscope.

2 Results and Discussion

2.1 Microstructures

2.1.1 Optical microstructures

Figs. 1(a) and 1(b) show the optical micrographs of the 1/4 longitudinal surfaces of NT-TQ500 and ST-TQ500, respectively. The microstructures were mainly composed of quasi-polygonal ferrite with anomalies in the grain boundaries, obviously different from typical polygonal ferrite, which exhibits smooth and straight grain boundaries. Small amounts of carbides were observed in the grain interiors and boundaries of NT-TQ500 and ST-TQ500. The mean grain size of ferrite in NT-TQ500 was measured to be 3.8 μm, close to that of ST-TQ500 (3.9 μm).

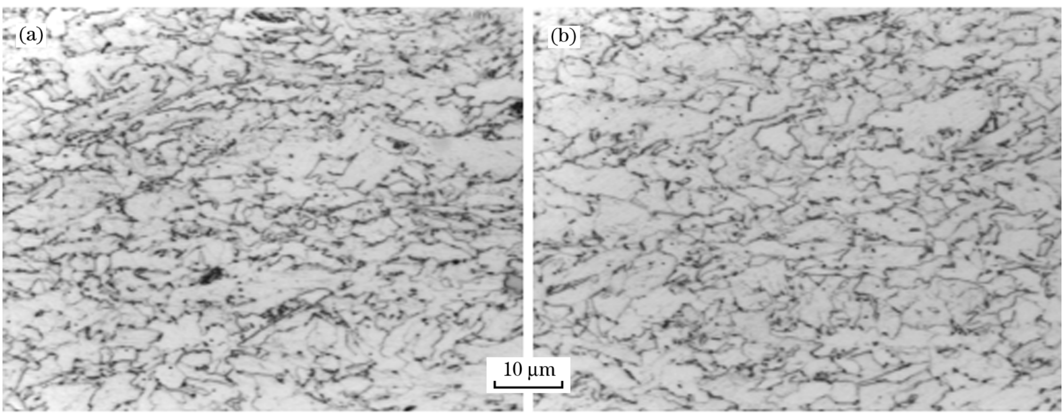

Fig. 1 Optical micrographs of the NT-TQ500 (a) and ST-TQ500 (b) samples

2.1.2 Submicroscale precipitates

To further analyze the differences between the carbides of NT-TQ500 and ST-TQ500, energy dispersive spectrometer (EDS) was used to compare