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Contribution of interphase precipitation on yield strength in thermomechanically simulated Ti–Nb and Ti–Nb–Mo microalloyed steels

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ABSTRACT

The contribution of interphase precipitation on yield strength was studied in Ti–Nb and Ti–Nb–Mo microalloyed steels. The high yield strength is partially attributed to strengthening induced by high degree of interphase precipitation of nanoscale carbides, which are nucleated during continuous cooling. The nanoscale carbides in Ti–Nb–Mo steel were identified as (Ti,Nb,Mo)C crystal structure similar to (Ti,Nb)C in Ti–Nb steel. The interphase precipitation of these carbides with planar or curved boundary, different row spacing and different orientation of the rows in the ferrite grain is related to the mobility of grain boundaries during γ/α transformation based on ledge mechanism. The contribution of interphase precipitation to yield strength was estimated to be ~320 MPa and ~170 MPa for Ti–Nb–Mo and Ti–Nb steels. The low yield ratio that is important from the perspective of structure application is attributed to the dual phase microstructural consisting of ferrite and bainite.

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1. Introduction

In recent years, since the development of microalloying concept, high strength low alloy (HSLA) steels have attracted significant interest in applications that include linepipe for transportation of oil and gas, building, bridges and automotive because of their superior mechanical properties. In engineering structure, steel component deformation capacity and load capacity can be significantly increased due to relatively low yield ratio, such as the ultimate bending strength is a key point that ensures structural safety of earthquake-resistant frames during major earthquakes. The most important aspect of microalloying elements is the ability to control and optimize the microstructure and consequently obtain the desired mechanical properties [1,2].

The precipitation of microalloying carbides contributed is of significant interest in HSLA steels. The underlying reason is that their size and distribution influence both yield strength and toughness. Thus, the alloy design and thermomechanical processing parameters need careful consideration. Interphase precipitation of fine carbides formed during γ/α transformation is generally recognized as an important mechanism for strengthening of hot-rolled microalloyed steels. The strength contributed by interphase precipitated carbides can approach 400 MPa according to previous studies [3,4]. Moreover, significant precipitation hardening can be obtained even at low volume fraction of precipitation (i.e., presence of low content of microalloying elements) [5]. Thus, compared to isothermal holding, tempering or quenching–tempering treatment, interphase precipitation during continuous cooling is an effective approach to obtain strength in microalloyed steels.

Interphase precipitation has generally been studied under isothermal conditions from several minutes to several hours. In the present study, we compare and analyze the precipitation behavior of carbides in HSLA steels containing Ti and Nb. The precipitation in the thermomechanically simulated material is examined in terms of chemistry, size, morphology, distribution and crystallography. Moreover, the strengthening mechanisms of interphase precipitates are analyzed, and the yield strength is calculated using empirical equations.

2. Experimental procedure

The chemical composition of the experimental steels is given in Table 1. A low carbon alloy design was studied. A Ti–Nb–Mo and Ti–Nb microalloyed steels (referred as A and B) were melted in a

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high frequency induction furnace and cast as 40 kg ingots. The ingots were forged into 80 mm thick square billet after soaking at 1200 °C for 2 h and thermomechanically processed using a laboratory-scale rolling mill. The billet was subjected to ~85% reduction to final thickness of 12 mm. The end temperature of the finish rolling was controlled to 835 °C, thereafter, the 12 mm thick plates was air cooled at a cooling rate of ~2 °C/s to 600 °C and then water-quenched to room temperature, as schematically shown in Fig. 1. The specimens for optical metallography were mechanically polished and etched in 3% nital. Transmission electron microscopy (TEM) foils were prepared by cutting slices from the plates, mechanically thinning to 0.05 mm, and twin-jet electropolishing to perforation using a solution of 5% perchloric acid and 95% ethanol at −20 °C. JEOL JEM-2100 TEM operating at 200 keV was used for examining foils. Vickers microhardness was measured at a load of 10 g from ~50 individual ferrite grains.

Table 1
Chemical composition of the experimental steels (wt%).

Type	C	Si	Mn	P	S	Ti	Nb	Mo
A	0.08	0.20	1.52	0.004	0.003	0.085	0.035	0.11
B	0.08	0.22	1.54	0.005	0.002	0.079	0.047	–

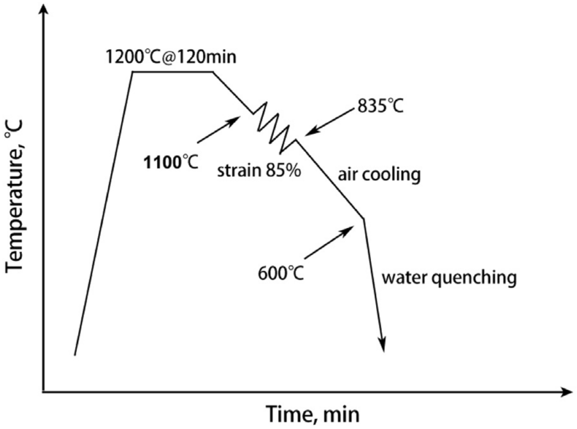

Fig. 1. Schedule diagram of deformation and thermal treatment.

3. Results and discussion

3.1. Optical metallography

Light micrographs of steels A and B are presented in Fig. 2 and comprise ~85% and 95% allotriomorphic ferrite, respectively. The balance dark etched phase is bainite, which originated from decomposition of the remaining austenite (Fig. 2). The formation of relative high percentage bainite in the Ti–Nb–Mo steel might have been due to the addition of the strong hardenability element Mo. Since this strong hardenability element has the ability to slow down the ferrite formation in the steel, the remaining untransformed austenite can further decompose into the bainite. The mechanical properties for the two experimental steels are present in Table 2. Table 2 shows that the tensile strength and the yield strength of Mo-containing steel are higher than the Mo-free steel.

3.2. Precipitation behavior

The precipitates observed in both the experimental steels were studied in terms of chemistry, location, size and morphology. The first type of precipitates formed during austenitizing are cubical shaped TiN particles, of size 200–500 nm, and do not contribute to strengthening. Some precipitates of spherical or elliptical particles identified as Ti-rich precipitates (Ti,Nb)CN were also observed of size range similar to TiN and are thermodynamically stable in austenite and ferrite and do not dissolve during soaking or hot rolling.

The second type of precipitates, which are the subject of interest in this study, were of nanoscale dimensions that primarily formed during γ/α transformation during the continuous cooling process. These precipitates, of size less than ~10 nm, contained Ti and Nb and were characterized by disk-shape morphology. They can be classified into two categories, interphase precipitates and random precipitates (Fig. 3). According to Misra's group [6], the interphase precipitation occurs at relatively higher temperatures,

Table 2
Mechanical properties of the experimental steels.

Type	TS (MPa)	YS (MPa)	Elongation (%)
A	974	747	16
B	731	487	24

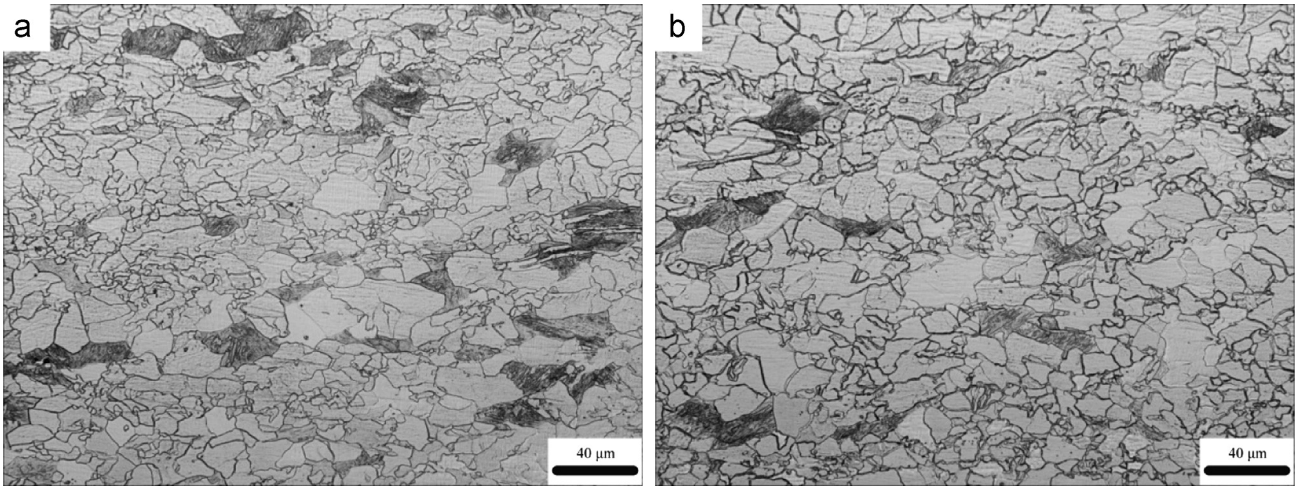

Fig. 2. Optical micrographs showing the microstructure of steel A and steel B.

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