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Effects of niobium and heat treatment on microstructure and mechanical properties of low carbon cast steels

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ABSTRACT

The present paper describes an attempt to reveal the effects of microalloying element niobium (Nb), normalizing and tempering temperatures on microstructure, strength and especially toughness of low carbon microalloyed cast steels. Four kinds of microalloyed cast steels with different contents of niobium have been examined by optical microscopy (OM), transmission electron microscopy (TEM), and electron back scatter diffraction (EBSD), tensile testing and room temperature Charpy V-notch impact toughness testing. As compared to Nb-free steel, the grains in the Nb-microalloyed cast steels are refined and the average grain sizes are about 20.8 ~ 34.6% lower. Moreover, fine spherical NbC precipitates with a diameter of about 1–15 nm are formed in the Nb-microalloyed cast steels. When normalized at 900 °C and tempered at 550 °C, the yield strength (YS) and ultimate tensile strength (UTS) of the microalloyed cast steel with 0.044 wt.% of Nb are increased to 350 MPa and 520 MPa from 290 MPa and 485 MP, respectively, as compared to Nb-free cast steel. Meanwhile, the impact energy is improved by 25.6% with ductility remained almost the same.

1. Introduction

Microalloyed steels, also known as high strength low alloy (HSLA) steels, are a class of steels containing small quantities of microalloying elements, such as niobium, vanadium, titanium and rare earth, either as a single addition or in combination. And the total amount of microalloying elements in these steels is generally less than 0.2% [1–3]. The initial development and research of microalloyed steels were driven by the demand for steels with higher strength and better weldability in the industries of construction, automobile and petroleum around the mid-1950s [4], and intense interest has been aroused among steelmakers, engineers and researchers all over the world since then. Most of the researches have focused on the following areas, such as effects of different microalloying elements on microstructure, properties and performances of microalloyed steels, the mechanisms of precipitation and strengthening, thermodynamics and kinetics of dissolution and precipitation, modeling and simulation of precipitation, heat treatment of microalloyed steels and etc. [5,6].

Vanadium, titanium and niobium were the first microalloying elements used to develop microalloyed steels because of their remarkable performance in steels. There have been a lot of researches and literatures on microalloyed steels with vanadium, titanium and niobium, either as a single addition or in combination. Rune Lagneborg et al. [7] reviewed the role of vanadium in microalloyed steels up to 1999, with an emphasis on its effects on microstructural evolution and mechanical properties. Later in 2009, T.N. Baker [8] published a comprehensive review on the process, microstructure and properties of microalloyed steels. Besides the historical background of vanadium microalloyed steels, some controversial topics on them were discussed in this review. Mariana Oliveira et al. [9] summarized the last 30 years' development of niobium steels in China. Moreover, many other papers, together with the book written by Q.L. Yong [3] and Gladman [4], covered the effects of vanadium, niobium and titanium on microstructure and properties of microalloyed steels. At the same time, much work [10,11] has been conducted and reported by Chinese scientists and engineers in the field of materials science about the effects of rare earth in steels since the late 1950s.

Except for grain refining, precipitation strengthening has been proven to be another main strengthening mechanism of microalloyed steels by numerous studies [12,13]. Therefore, thermodynamics and kinetics, as well as modeling and simulation of precipitation have attracted more and more attention of researchers in the field of materials science. J. G. Speer et al. [14] provided a detailed study on carbonitride precipitation in niobium/vanadium microalloyed steels and a thermodynamic model of (Nb, V) (C, N) precipitation. W. J. Liu [15] introduced a kinetic model of strain-induced precipitation of Nb(C, N) in microalloyed austenite. A method on predicting the inhomogeneous distribution of microalloyed precipitates in high strength low alloy continuous cast slabs was presented by Suparna Roy et al. [16].

The development of microalloyed cast steels was later than that of the hot or cold worked microalloyed steels. Moreover, there are much

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fewer reports on microalloyed cast steels as compared with plastically deformed microalloyed steels. Since microalloyed cast steels are produced without plastic deformation, optimization of the heat treatment process is the most commonly used way to improve their properties and performances. Therefore, the researches on microalloyed cast steels have been focusing mainly on the influences of microalloying elements and different heat treatment processes on microstructural evolution and mechanical properties. Microalloyed cast steels with Nb, V, Ti or rare earth have become one of the most popular subjects to materials scientists since the last few decades. The studies on heat treatment processes for microalloyed cast steels can be summarized as homogenization, austenization followed by quenching, fan cooling or air cooling, and tempering. For the large-scale steel castings, normalizing and tempering are often adopted since good maneuverability and cost effectiveness are involved in actual production.

It is generally reported that the strength of microalloyed cast steels can be significantly improved by many researchers, but the variations of toughness and ductility are not consistent. The study of Ma Jie et al. [17] showed that the strength of the cast steels could be significantly improved with Nb, V, Ti and rare earth, either as a single addition or in combination. However, there was no obvious regularity in the variation of ductility and toughness after the microalloyed cast steels were normalized at 950 °C and tempered at 650 °C. Hamidreza Najafi et al. [18, 19] studied the effects of niobium, vanadium, titanium on mechanical properties of as-cast low carbon steels. They indicated that the yield strength and ultimate tensile strength were enhanced at the expense of room temperature impact toughness by microalloying, meanwhile the fractography of the investigated steels were changed to the dominance of cleavage facets. The work by B. Chokkalingam et al. [20] also proved that the toughness would be deteriorated when the steels were microalloyed with niobium and vanadium. Since many large-scale steel castings are employed at low temperature or impact load conditions, it is essential to improve their room or low temperature toughness. In order to get a better understanding of the effects of microalloying elements on microstructure and mechanical properties, especially toughness, as well as the composition/process-microstructure-property relationships of microalloyed cast steels, a lot of systematic investigations are still required.

The current work aims to explore a process which can improve both the strength and toughness of microalloyed cast steels and tries to reveal the composition/process-microstructure-property relationships. Four kinds of low carbon microalloyed cast steels with different Nb contents were melted in the air and treated with different normalizing and tempering temperatures. The strength and toughness of all the experimental steels were measured. Then OM, SEM, and TEM techniques were adopted to analyze the effects of microalloying element Nb and different heat treatment processes on microstructure. The characteristics of grains and precipitates of the microalloyed steels were quantitatively examined by electron back scatter diffraction (EBSD) and selected area electron diffraction (SAED). Finally, an optimized process of microalloying and heat treatment was offered for the production of large-scale Nb-microalloyed steel castings.

2. Experimental procedure

2.1. Chemical composition and process

The compositions of the experimental steels are listed in Table 1. The steels were air melted with scraps in a 50 kg capacity medium frequency induction furnace. After complete melting of the base metal, graphite and ferromanganese were added to the melt to increase the contents of carbon and manganese. Then, ferrosilicon was added for the purpose of pre-deoxidation and adjusting the silicon content. Microalloying elements were added to the melt in the form of ferroniobium. Finally, the melt was aluminium killed by adding commercial purity aluminium in the ladle. The major compositions of the heats were designed to be 0.15 to 0.20 wt.% carbon, 0.40 to 0.60 wt.% silicon and 0.75 to 0.95 wt.% manganese with the contents of residual sulfur and phosphorus below 0.03 wt.% and 0.01 wt.%, respectively. The Nb contents of the microalloyed heats were selected to be 0.01 to 0.10 wt.%. The heats were poured into the ladle at the temperature of 1640 °C to 1660 °C. Then, the heats in the ladle were poured into the sand mould to produce the Keel Blocks. At the same time, the actual compositions of the experimental steels were analyzed with a Germany FXL59S0112 spectrometer. After cooling, the Keel Blocks were cut into parts to investigate the microstructure and mechanical properties of microalloyed steels in the as-cast and heat-treated state. Heat treatment process parameters for the specimens are given in Table 2. Samples for microstructure characterization and mechanical property testing were cut from the ingots by wire cutting electro discharge machining, as shown in Fig. 1.

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

Steel	C	Si	Mn	P	S	Al	V	Nb
1	0.179	0.490	0.826	0.0211	0.0049	0.072	0.009	–
2	0.154	0.550	0.902	0.0230	0.0076	0.058	0.010	0.016
3	0.182	0.417	0.942	0.0198	0.0060	0.029	0.011	0.044
4	0.150	0.463	0.758	0.0182	0.0027	0.052	0.010	0.072
5	0.203	0.409	0.796	0.0171	0.0018	0.051	0.012	0.097

2.2. Microstructure characterization

Samples for metallographic examination were prepared using standard grinding and polishing techniques and etched with a solution of 3% (volume fraction) nital. Then, the etched samples were observed under an MM6 horizontal metallographic microscope to study the constitution and morphology of microstructures at the magnification of 100 times.

Samples for the EBSD study were prepared by grinding, mechanical polishing and final electropolishing with a solution of 10% (volume fraction) perchloric acid and 90% (volume fraction) ethanol, using a voltage of 28 V for 50 min under the temperature region of −30 to −20 °C. The samples were cleaned with water and ethanol immediately after electropolishing and kept in the ethanol. Then EBSD collections were conducted to examine the grain morphology and size distribution of the experimental steels under the FEI QUANTA 200 environment scanning electron microscope.

For further TEM examination, slices of 500 μm in thickness were cut from the ingots using a wire cutting electro discharge machine. These samples were subsequently ground to 100 μm in thickness and discs of 3 mm in diameter were punched from the thin wafers. Then, the discs were ground to the thickness of about 40 μm. Finally, TEM foils were prepared by electropolishing the discs in a Fischione twin jet unit. The solution for electropolishing was 10% (volume fraction) perchloric acid and 90% (volume fraction) ethanol. The foils were examined under a JEOL 2100 transmission electron microscope with an energy dispersive X-ray spectrometry attachment operated at 120 kV to

Table 2
Heat treatment and mechanical properties of the experimental steels.

Steel	Normalizing temperature (°C)	Tempering temperature (°C)	YS (MPa)	UTS (MPa)	Elongation (%)	Room temperature Charpy-V notch impact energy (J)
1	900	550	290	485	34.5	95.3
2	900	550	295	485	39.5	129.7
3–1	–	–	315	515	18.5	14.0
3–2	900	550	350	520	32.5	119.7
3–3	900	650	330	495	32.5	104.0
3–4	950	650	320	490	34.0	112.3
4	900	550	325	490	32.0	133.0
5	900	550	325	495	28.5	70.0