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Effect of normalizing temperature on microstructure and mechanical properties of a Nb-V microalloyed large forging steel

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A B S T R A C T

The microstructure of a microalloyed large forging steel with different normalizing temperatures ranging from 820 °C to 940 °C were characterized. The evolution of austenite formation was determined in a range of heating temperature from 730 °C to 940 °C. The mechanical properties were evaluated by tensile test and Charpy V-notch impact test. The relationship between the microstructure and the properties was discussed. The results indicated that the microstructure composed of fine-grained layers (FGL) and coarse-grained layers (CGL) was obtained at 820 °C. The finest and most homogeneous microstructure and optimal comprehensive mechanical properties were obtained at the normalizing temperature 880 °C. There was a Hall-Petch relationship between the yield strength and the average grain size, and a linear relationship between the impact energy (KV_2) and the reciprocal of the square root of the grain size ($D^{-1/2}$). Both the strength and toughness of the steel can be attributed to grain refinement.

1. Introduction

Microalloyed large forging steel has been widely used for engineering components which require high strength, good toughness and large size. Large forging steel is usually made from large casting ingots. The as-forged microstructure of the steel is generally composed of coarse ferrite and banded pearlite which consequently lead to limited impact toughness. Due to the characteristic of forging process and the large volume of forging, conventional technology such as thermo-mechanical treatment or accelerated cooling is infeasible for grain refinement in order to improve toughness.

However, it is likely to increase toughness levels of microalloyed large forging steel through grain refinement by normalizing. Zhao et al. [1] studied the effect of W addition and normalizing conditions on microstructure and mechanical properties of microalloyed forging steels, four kinds of microalloyed forging steels were produced by varying W additions (0, 0.5, 1 and 2 wt%), heat treatment was carried out at temperatures ranging from 840 °C to 950 °C followed by air and furnace cooling, the results showed that the microstructure and mechanical properties of the microalloyed forging steels were closely related to the W content, normalizing temperature and cooling method after normalizing. Zhao et al. [2] studied the effect of hot forging, normalizing temperature (840–950 °C) and cooling method (air and furnace cooling) after normalizing on the toughness and tensile properties of a microalloyed cast steel, the results showed that remarkable improvement in toughness and tensile properties can be obtained by hot forging, proper normalizing temperature and air cooling after normalizing. Zhao et al. [3] studied the effect of normalizing temperature (950–1200 °C) and cooling method (furnace, air and water cooling) after normalizing on the toughness and tensile properties of a low-carbon microalloyed cast steel, the results showed that heat treatment at 1100 °C for 2 h followed by furnace cooling leaded to the best combination of excellent Charpy impact and tensile properties.

The above research focused on the low carbon Nb-Ti microalloyed steel, there was no many studies on Nb-V microalloyed steel in which the V content can be as much as 0.1 wt%. Besides, the sizes of samples used by Zhao et al. [1–3] were $11 \times 11 \times 60\ mm^3$ or $11 \times 11 \times 110\ mm^3$, the air cooling rate was above 3 °C/s. There were rare studies on large section forging steel with the diameter larger than 250 mm and the air cooling rate below 0.05 °C/s. Austenite formation in low carbon steels has been studied extensively in the literature starting from different microstructures [4–6]. Previous work has shown that in ferritic-pearlitic microstructures the formation of austenite was described as taking place in three main successive steps: (1) nucleation of austenite in pearlite colonies, ferrite-pearlite grain boundaries or ferrite-ferrite grain boundaries, (2) rapid growth of austenite consuming pearlite, (3) slower growth of austenite consuming

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ferrite [7,8]. Based on the above theory, as for ferrite-pearlite banded microstructure in large forging steel, austenization in ferrite bands and pearlite bands are asynchronous. Nonetheless, rare literature has studied this phenomenon. What's more, there were no many studies on the effect of intercritical normalizing on microstructure and mechanical properties of Nb-V microalloyed large forging steel.

For large forging steel, it is impracticable to enhance cooling rate in case of thermal stress-cracking. The cooling method followed normalizing is usually air cooling, hence the austenization temperature is the decisive normalizing parameter for microstructure and properties. The study of this paper aims at investigating the effect of normalizing temperature on microstructure and properties of a Nb-V microalloyed large forging steel. The evolutions of austenite, microstructure and precipitations of the tested steel were characterized. The relations between the microstructure and properties were discussed. The tested steel in this work with the diameter of Φ290 mm and the V content up to 0.095 wt% has never been investigated.

2. Experimental material and procedures

The steel used in this work is a commercial HSLA steel. The chemical composition is listed in Table 1. The round bar specimens with a length of 200 mm and diameter 290 mm for normalizing is shown in Fig. 1. They were cut from a Φ290 mm round forging. In order to study the characteristic of microstructure at the corresponding normalizing temperature, cubic samples for quenching were wire-cut from the 1/2 radius of the Φ290 mm round forging. The size of the quenching samples is 10 × 10 × 12 mm^3. Both the normalizing and quenching process was conducted in a 45 kW box resistor-stove, the schedules of the process are given in Fig. 2. The normalizing specimens were reheated at 820 °C, 850 °C, 880 °C, 910 °C and 940 °C with soaking for 2 h, respectively, and then were cooled by air with about a 0.03 °C/s cooling rate. In order to study the evolution of austenite, samples for interrupted heating by quenching were respectively reheated at 730 °C, 760 °C, 790 °C, 820 °C, 850 °C, 880 °C, 910 °C and 940 °C holding for 2 h.

After the normalizing process, blanks for metallographic observation and mechanical property test were wire-cut from the 1/2 radius of the normalizing samples along longitudinal axial direction as shown Fig. 1. Metallographic observation direction for all test samples was parallel to the longitudinal section of the Φ290 mm round forging. The microstructure of the samples was etched by a 4% nital solution. The size and area fraction of ferrite and pearlite constituent were measured by software Image-Pro Plus. For each specimen, at least 5 fields of view containing at least 400 grains were measured. Thin foils for Transmission Electron Microscopy (TEM) were prepared using the twin-jet method and observed in a JEM-2100 transmission electron microscope. The average size and fraction of precipitate particles were statistically measured by averaging 5 fields of view containing at least 300 particles from the images of TEM. In order to study the orientation characteristic of acicular pearlite, electron back scattered diffraction examinations were performed on a field emission gun scanning electron microscope.

The blanks for tensile test were machined into standard tensile test specimens of 10 mm in gage diameter and 50 mm in gage

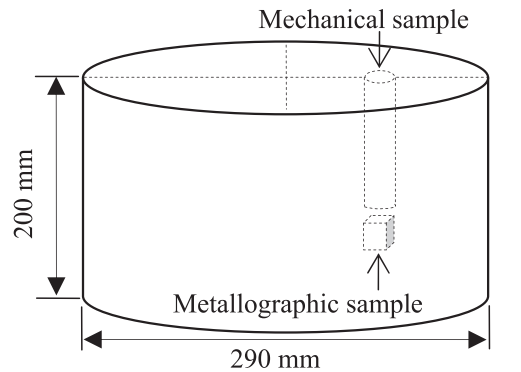

Fig. 1. The normalizing sample and sampling method.

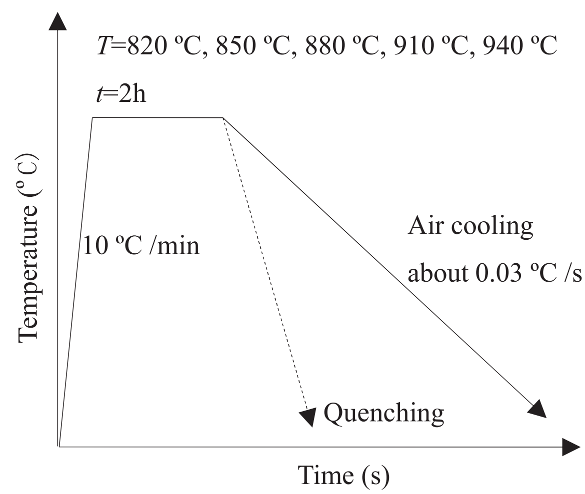

Fig. 2. Normalizing and quenching process.

length. Tensile tests based on standard of ISO 6892-1:2009 were carried out on a WDW-200D tensile testing machine at room temperature with a cross-head speed of 0.25 mm min^{-1} [9]. The yield strength was determined by the 0.2% offset flow stress. All results were repeated for three times and the average values were taken to describe the tensile properties of the test steel. The Charpy V-notched specimens with cross section of 10 × 10 mm^2, length of 55 mm, notch angle of 45° and notch depth of 2 mm were employed to study the −40 °C impact fracture toughness on a ZBC2452-B impact testing machine according to ISO 148-1:2006.

3. Results and discussion

3.1. The evolution of austenite formation

The study of the austenite formation was carried out using a DIL805A high resolution dilatometer. Cylindrical samples of 4 mm diameter and 10 mm length were used for the experiments. As shown in Fig. 3, the relations between heating temperature(T) and expansion amount (ΔL) were analyzed to determine A_{c1} and A_{c3} at a constant heating rate of 10 °C/min. Since some investigations have experimentally shown that a separation can be made between the pearlite to austenite and the ferrite to austenite transformation [10–12], an attempt was made to determine the temperature ($A_{c\theta}$) at which this occurred. The determination of $A_{c\theta}$ can be only attempted if the first contraction is perceived. It is less evident to see from the dilatometric curve, but easier to determine from the first derivative ($d\Delta L/dT$) as shown in Fig. 3. In previous papers studied similar steels, the authors showed that this first

Table 1
Chemical compositions of the tested steel (wt%).

C	Si	Mn	P	S	Nb	V	Ti
0.15	0.27	1.45	0.01	0.004	0.045	0.095	0.01