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Effects of tungsten on continuous cooling transformation characteristics of microalloyed steels

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ABSTRACT

Continuous cooling transformation (CCT) characteristics of microalloyed steels with different tungsten (W) contents (0, 0.1 and 1 wt.%) were investigated to obtain the necessary information for heat treatment of these steels. The effects of W addition on the sizes of prior austenite grains and precipitates were analysed. CCT diagrams were obtained by varying the cooling rates from 0.1 to 120 °C/s. Transformation characteristics were determined by using dilatometer test, microscopic observation and hardness measurement. The results showed that W had a positive effect on the refinement of prior austenite grains and precipitates. The CCT diagrams exhibited that the ranges of transformation products were shifted to the right side of the diagram when the W content increased. CCT diagram for steel with 0.1% W was similar in shape to that without W. The addition of 1% W induced two separated transformation ranges in the cooling rate range of 0.1 to 1 °C/s in the diagram. Both the austenitisation starting and finishing temperatures were raised as W was added. W addition induced decreased critical cooling rates for phase transformations and obtaining complete ferrite + pearlite microstructures. The martensite transformation temperature was decreased after W addition. The addition of W caused increased hardness, and the hardness obeyed an exponential type relationship with cooling rate.

1. Introduction

Microalloyed steels are widely used in the fields of oil and gas extraction [1], construction [2] and transportation [3]. Several aspects of microalloyed steels, including heat treatment [4], phase transformation [5,6], mechanical properties [7,8] and oxidation behaviours [9], have been studied over the past decades. Multiple microstructures in microalloyed steels obtained depend on the states of the austenite prior to the transformations, chemical compositions and cooling conditions. Different microstructural combinations bring about drastic change in the mechanical properties. Austenite is the parent phase of all the microstructures including pearlite, proeutectoid phases, bainite, matensite and various ferritic microstructures [10]. Depending on chemical composition and cooling rate, the austenite of a given microalloyed steel could transform to all of the listed microstructures. The microstructures of austenite transformation products depend on austenite grain size. Refinement of austenite grain size in microalloyed steels is critical in producing the final refined microstructures with high strength and toughness. By adjusting the chemical compositions, the mechanical properties of microalloyed steels can be significantly tailored. Previous studies have been carried out about the effects of alloying elements on the microstructures and mechanical properties of these steels. Balart et al. [11] studied the effect of Si and Ti on the microstructure and mechanical properties of V-microalloyed steel. They found that Si and Ti additions show positive effect in increasing the strength and refining the austenite grain size, respectively. As reported by Najafi et al. [12], the presence of microalloying elements significantly enhanced the strength of as-cast microalloyed steels due to the formation of fine-scale precipitates. The work of Han et al. [13] indicated that precipitates affect the hot ductility of microalloyed steels.

Cooling procedure is one of the most important processing factors affecting the mechanical properties of microalloyed steels after heat treatment or hot working. A fast cooling rate depresses the transformation temperature and refines precipitate size, and hence increases the hardness of microalloyed steels [14]. The microstructure is changed from ferrite/peatlite to bainitic ferrite with an increase of cooling rate, and such microstructural change is responsible for the high strength–toughness combination of microalloyed steels at high cooling rate [15]. The work of Rasouli indicated that the best combination of strength and ductility of microalloyed forging steel can be obtained by adjusting the microstructural component through control of the cooling rate [16].

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Tungsten (W) is a strong ferrite former, and is effective for precipitate refining and solid solution strengthening. As the content of W increases in alloy steels, W forms very hard, abrasion-resistant carbides, which can prevent grain growth at high temperature. In microalloyed steels, the microstructures and mechanical properties are greatly dependent on the W contents [17,18]. The transformation characteristics in W-containing microalloyed steels under different cooling conditions become more complicated relative to those of W-free microalloyed steels due to the significant effect of W on the microstructural evolution. For obtaining the best combination of excellent strength and toughness which are closely related to the microstructures, it is essential to investigate the transformation characteristics at various cooling rates to obtain the necessary information for heat treatment and hot working of these steels. Unfortunately, the effects of W on the microstructural evolution of microalloyed steels at different cooling rates have not been well reported, and no detailed mechanism for these is presented.

A review of the effects of some allying elements (including W, Cr, V, Mo etc.) on the transformation diagrams was presented in an earlier paper [19]. All these studies were conducted under isothermal conditions. For application to most practical processes, however, continuous cooling transformation (CCT) data are needed. The aim of this study is to systematically investigate the CCT characteristics of microalloyed steels with different W contents. The effects of W addition on the prior austenite grain size will be investigated first, and CCT diagrams of microalloyed steels with different W contents will be presented. The hardness change and microstructural evolution with cooling rates will also be analysed. Particular discussion will be made on the dependence of microstructural combination on the W content and cooling rate.

2. Experimental procedure

Three kinds of microalloyed steels with different W contents (0, 0.1 and 1 wt.%) were used in this study. The chemical compositions of the steels are given in Table 1. Ingots were homogenised at 1230 °C for 1 h and then hot forged to be a cube with section size of 140 mm × 140 mm and height of 400 mm followed by air cooling. The final forging temperature was controlled to be higher than 950 °C. Cylindrical dilatometer specimens with a diameter of 3 mm and height of 10 mm were machined from the forged pieces.

Different phases, such as austenite and ferrite, in steels have distinctly different specific volumes. Hence, it is possible to differentiate the volume change (length change) when phase transformation occurs from the linear thermal expansions during heating and cooling of steels by employing a high resolution dilatometer. In the present study, dilatometer specimens were heated to the temperature of 950 °C at a rate of 20 °C/s, then held for 10 min, and finally cooled to room temperature at different linear cooling rates ranging from 0.1 to 120 °C/s. The schedule for dilatometer tests is schematically shown in Fig. 1. Dilatometer tests were conducted on a Theta Dilatronic III dilatometer. The specimens were heated and cooled under a vacuum of 5×10^{-4} mbar to prevent oxidation.

During phase transformation, the specimen expands during cooling although the temperature decreases as a result of the microstructure rearrangement. A typical dilatation vs. temperature curve of 1W steel at the cooling rate of 0.5 °C/s is shown in Fig. 2. The up and down arrows indicate the progress of heating and cooling cycles, respectively. From this curve, the start and finish of a phase transformation can be easily detected. However, as the start of pearlite transformation cannot be clearly detected on the dilatation–temperature curve [20,21], metallographic observation is needed to determine the starting temperature of pearlite transformation. In this research, all the specimens after dilatometer tests were subjected to detailed microscopic observation and hardness measurements to ensure that every phase transformation temperature was accurately determined.

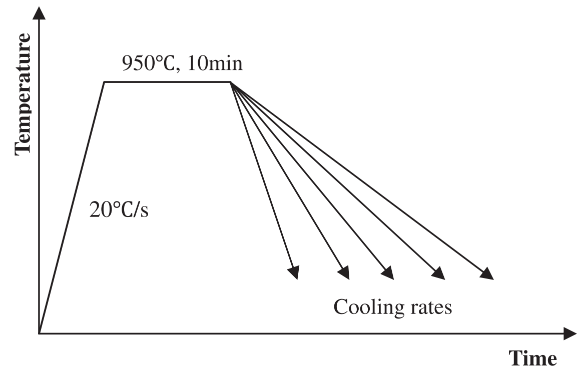

Fig. 1. Schematic illustration of the schedule for dilatometer tests.

Metallographic specimens were etched with 2% nital solution for microstructural observation by an OLYMPUS BX51M optical microscope (OM). Hardness was measured with a Vickers hardness tester using 2 kg load and 10 s dwelling time, and six indentations for every specimen were randomly made on its surface. For observing prior austenite grain boundaries, specimens were re-heated to 950 °C at a rate of 20 °C/s for 10 min followed by water quenching. The water quenched specimens were etched with a "picric acid + $FeCl_3$ + dodecyl benzene sulfonic acid sodium salt" solution to reveal prior austenite grain boundaries, and then observed by OM. To examine the characteristics and compositions of precipitates in the water quenched specimens, extraction replicas as well as thin foils mounted on Cu grids specimens were prepared and analysed using energy dispersive X-ray spectroscopy (EDS) method on JEOL JEM-2100F transmission electron microscope (TEM) operated at 200 kV.

3. Results

3.1. Prior austenite grains

Fig. 3a and b presents the prior austenite grains of the water-quenched 0W and 1W steels after holding at 950 °C/s for 10 min, respectively. It can be seen that the addition of 1% W induces finer austenite grains in contrast to that in 0W steel. The average austenite grain sizes of the 0W and 1W steels were determined as 15.8 and 10.7 μm, respectively, by using circular intercept method according to ASTM: E112-10. W addition shows a positive effect on decreasing the austenite grain size.

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

Steels	C	Mn	Cr	Ni	Cu	Si	Al	V	Nb	Ti	P	S	N	W
0W	0.171	1.22	0.103	0.025	0.023	0.469	0.019	0.015	0.023	0.019	0.013	0.008	0.007	0
0.1W	0.170	1.20	0.103	0.024	0.024	0.471	0.024	0.015	0.023	0.020	0.014	0.009	0.008	0.09
1W	0.171	1.20	0.112	0.024	0.022	0.499	0.021	0.016	0.020	0.020	0.008	0.008	0.006	0.99