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Investigation on grain refinement and precipitation strengthening applied in high speed wire rod containing vanadium

Da-yong Wu, Fu-ren Xiao, Bin Wang, Jia-ling Liu, Bo liao*

The Key Laboratory of Metastable Materials Science & Technology, College of Materials Science and Engineering, Yanshan University, Qinhuangdao 066004, China

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ABSTRACT

To obtain necessary information for the simulation of high speed wire production process, the effect of grain refinement and precipitation strengthening on two high speed wire rod steels with different vanadium and nitrogen contents was investigated by continuous cooling transformation (CCT) characteristics. CCT curves were constructed by the dilatometer test and microscopic observation. Results showed that the formation of intra-granular ferrite (IGF) could refine grain remarkably and accelerate the ferrite transformation. Schedules for high speed wire production process focused on the effect of cooling rate. Ferrite grain was refined by increasing cooling rate and the formation of IGF. The microhardness calculation revealed that the steels were strengthened mostly by a combined effect of grain refinement and precipitation hardening. Degenerated pearlite was observed at lower transformation temperature and the fracture morphology changed from cementite lamellar to nanoscale cementite particle with increasing cooling rate. Based on the analysis above, an optimal schedule was applied and the microstructure and microhardness were improved.

1. Introduction

High speed wire rod is one of the largest demand and the largest steel production, which has been widely used in reinforced concrete building, wire for welding, communication equipment, suitable screws or fasteners, etc. Recently many efforts have been made to improve the structural performance and extend the applications by enhancing strength and toughness [1–5].

In the high speed wire production process, the grain refinement and precipitation strengthening controlled by cooling procedure and alloy addition are efficient on improving the mechanical properties of microalloyed steels after rolling. Particularly under a higher cooling rate, the increased nucleation density due to lowering ferrite transformation restricts grain growth because of impingement of mutual grains, and consequently results in ferrite grain refinement. Recent studies [6,7] strongly suggest that vanadium can also be effectively used for ferrite grain refinement. Although, V does not readily precipitate in austenite, the precipitation process can be promoted by increasing N or by plastic deformation (strain induced precipitation), which show strong potential for nucleation of IGF. Meanwhile, V in structural steels is usually considered as the preferred element when precipitation strengthening is required [8,9]. Due to its strong solute solubility, vanadium carbide (VC) usually precipitated after transformation and precipitation hardening stress provided by these nano-sized particles can achieve ~600 MPa [10]. Besides the formation of low transformation temperature product, degenerated pearlite, has also received more attentions owing to its exceptional toughness [2,11].

Therefore, design for composition and thermo-mechanical controlled processing is of growing importance for concerns with maximization of precipitation strengthening effect and the microstructure refinement. In present work, two medium carbon steels, the composition closed to an automotive fastener steel, were chosen and a series of schedules were applied to simulate the industrial high speed wire rod production process to investigate ferrite grain refinement and precipitation hardening.

2. Experimental materials and procedures

The materials used in this study were cast in a vacuum induction furnace, and subsequently the cast slabs were hot forged and rolled to the bars of 18 mm diameter. The final specimens (Gleeble specimen) were rod shaped specimens of 8 mm diameter and 12 mm gauge length. The chemical composition of steel A was fixed as C—0.17, Si—0.51, Mn—1.4, V—0.10, N—0.0031, Ti—0.02 and Fe—balance (wt%). Compared with steel A, V decreased to 0.05 wt %, but N increased to 0.015 wt% in steel B. For the Ti addition, due to its higher solution temperature [12] and lower content, the

* Corresponding author. Tel./fax: +86 3 358 077 110.
E-mail addresses: frxiao@ysu.edu.cn (F.-r. Xiao), cyddjyjs@263.net (B. liao).

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effect of Ti on precipitation and its precipitates effect on hardness was neglected.

Dilatometer experiments were carried out on the Gleeble-3500 hot simulator to determine the temperature interval for the transformation at varying cooling rates to provide data for construction of CCT curves. For CCT determination, all dilatometer samples were first reheated in a furnace at 1150 °C in a vacuum environment for 5 min, followed by cooling at 10 °C/s to 900 °C and deformed 40% to refine the austenite grain structure, and thereafter cooled at 0.3, 1, 5, 10, 20 and 40 °C/s to room temperature. Besides, some quenched specimens before deformation were obtained to observe the precipitation. Based on the CCT curves, some samples quenched blow A_{r3} temperature ~10 °C were gained to investigate the forming of IGF respectively.

The thermomechanical controlled processing of Φ 8 mm high speed wire rods was simulated by first reheating specimens in vacuum at a rate of 10 °C/s to 1150 °C and holding for 5 min before subjecting them to the following hot deformation schedules: cooling at 10 °C/s → 1000 °C deformation 40% with strain rate 1 s^{-1} (rolling temperature) → cooling at 50 °C/s → 850 °C (spinning temperature) → cooling at 1, 5, 10 °C/s → 640 °C (volume temperature) → cooling at 0.083 °C/s → 550 °C → air cooling to room temperature. The purpose of this was to simulate as closely as possible an industrial high speed wire rod production process, including the final coiling treatment. The experimental parameters were established based on the analysis of CCT curves.

Specimens for metallographic examination were mechanically polished and etched with a 3% nital solution, and then observed with an optical microscopy. The CCT diagrams of the tested steels were constructed from a combination of optical micrographs and the cooling dilatation curves. Thin foils were made from a selection of the samples by electropolishing and these were examined in JEM-2010 TEM at 200 kV. The grain size was measured applying ASTM standard E-112 and the Vickers hardness of the heat treated specimens was measured by using a load of 50 gf. After holding 5 min at 1150 °C, the austenite grain boundaries of the quenched specimens were observed by etching in an aqueous solution of picric acid and 40, 36 μm was gained for steels A and B respectively.

3. Results

3.1. The continuous cooling transformation of testing steels

Fig. 1 shows the microstructures of the testing steels obtained after deformation in austenite and subsequent cooling with different rates. Fig. 1(a) shows the microstructure of massive equiaxed ferrite, pearlite and a little granular bainite at the cooling rate 0.3 °C/s in steel A. Compared with the microstructure obtained at 0.3 °C/s, the amount of ferrite and pearlite in steel A at the cooling rate 1 °C/s was decreased, replaced by granular bainite. Meanwhile, part of ferrite changed from being equiaxed to be acicular. When the cooling rate increased to 5 °C/s, the microstructure of steel A was composed of granular bainite, bainite ferrite, a little ferrite and retained austenite, as shown in Fig. 1(c).

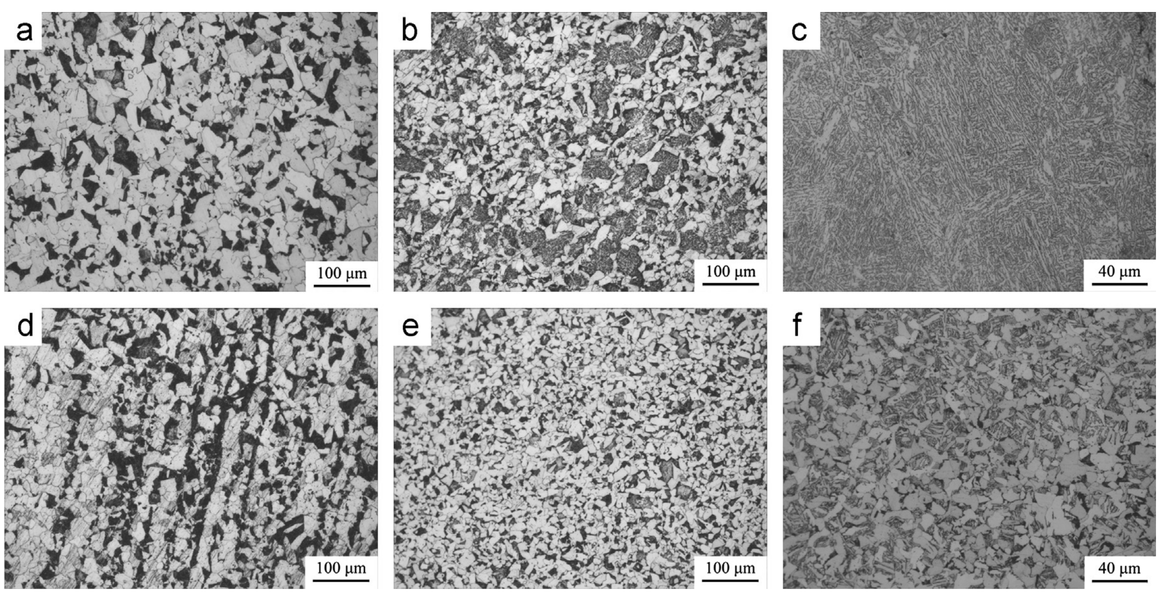

Fig. 1. Transformation microstructures of testing steels under different cooling rates (steel A: (a) 0.3 °C/s, (b) 1 °C/s, (c) 5 °C/s; steel B (d) 0.3 °C/s, (e) 1 °C/s, (f) 5 °C/s).

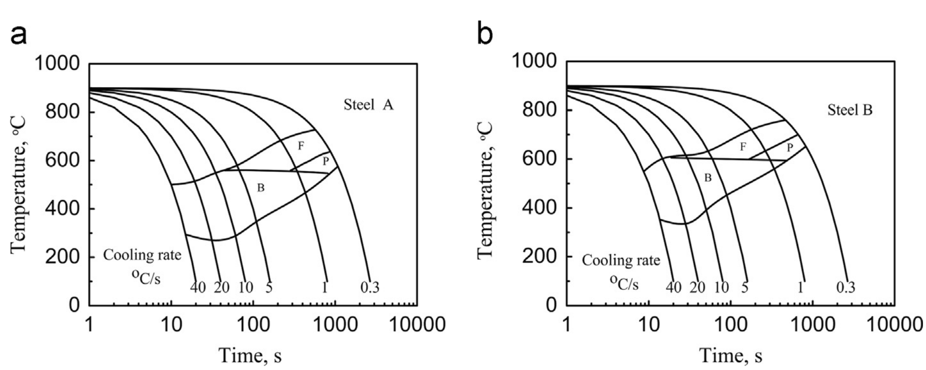

Fig. 2. CCT diagrams of testing steels: (a) steel A and (b) steel B.