Materials and Design 53 (2014) 332–337

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Cooling process and mechanical properties design of hot-rolled low carbon high strength microalloyed steel for automotive wheel usage

Jun Hu [a,*], Lin-Xiu Du [a,*], Jian-Jun Wang [b], Qing-Yi Sun [c]

[a] The State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, China
[b] Institute of Materials Research, School of Material and Metallurgy, Northeastern University, Shenyang 110819, China
[c] WISDRI Engineering & Research Incorporation Limited, Wuhan 430223, China

ARTICLE INFO

Article history:
Received 17 November 2012
Accepted 4 July 2013
Available online 20 July 2013

Keywords:
Steel design
Microstructures
Mechanical properties
Automotive wheel steel
Cooling schedule
Strengthening mechanism

ABSTRACT

For the purpose of developing Nb–V–Ti microalloyed, hot rolled, high strength automotive steel for usage in heavy-duty truck wheel-discs and wheel-rims, appropriate cooling processes were designed, and microstructures and comprehensive mechanical properties (tension, bending, hole-expansion, and Charpy impact) of the tested steels at two cooling schedules were studied. The results indicate that the steel consists of 90% 5 μm polygonal ferrite and 10% pearlite when subjected to a cooling rate of 13 °C/s and a coiling temperature of 650 °C. The yield strength, tensile strength, and hole-expansion ratio are 570 MPa, 615 MPa, and 95%, respectively, which meet the requirements of the wheel-disc application. The steel consists of 20% 3 μm polygonal ferrite and 80% bainite (granular bainite and a small amount of acicular ferrite) when subjected to a cooling rate of 30 °C/s and a coiling temperature of 430 °C. The yield strength, tensile strength, and hole-expansion ratio are 600 MPa, 655 MPa, and 66%, respectively, which meet the requirements of the wheel-rim application. Both the ferrite–pearlite steel and ferrite–bainite steel possess excellent bendability and Charpy impact property. The precipitation behavior and dislocation pattern are characterized and discussed.

1. Introduction

Recently, metallurgists have been engaged in developing as-hot-rolled steels in place of conventional quenched and tempered steels [1–2]. Quenched and tempered steels can be substituted by microalloyed steels in cases where microalloyed steels possess equivalent strength and toughness [3]. Moreover, for the purpose of obtaining good toughness and weldability, carbon content is reduced, and the resultant decrease in strength is compensated for by the addition of Si and Mn [4]. A further increase in strength is acquired through precipitation hardening and fine grained hardening by microalloying with low cost Nb, V, and Ti, individually or complexly [5]. Nowadays, the as-hot-rolled high strength steels have been widely developed and utilized for structural applications such as buildings, bridges, offshore platforms, and automobile components [4,6–9].

Automotive wheel steel requires excellent comprehensive mechanical properties. In order to reduce wheel weight of heavy-duty trucks and meet the demand for safety simultaneously, the strength and ductility of the as-hot-rolled microalloyed steels must be well-balanced. Thus, the mechanical properties evaluations are achieved with various tensile tests, bending tests, hole-expansion tests, and Charpy impact tests [10–11]. The mechanical properties depend on the microstructural type, proportion, and morphology, which are influenced by the cooling procedure [12–15]. In general, automotive wheel-discs require better ductility compared to wheel-rims, while steel with higher strength has more potential to reduce the weight of the wheel. Therefore, in order to make most efficient use of the material, it is meaningful to develop automotive wheel-disc steel and wheel-rim steel, which are subjected to different cooling procedures, but utilize the same raw materials. This design idea could reduce the difficulty of welding wheel-discs and wheel-rims, due to them having the same chemical composition.

The present work is aimed at designing low-cost Nb–V–Ti microalloyed high strength steels possessing two strength and ductility regulations without adding expensive elements, such as Mo, Cr, Ni and Cu. The microstructural evolution, precipitation behavior, and dislocation pattern are described. Furthermore, the comprehensive mechanical properties (tension, bending, hole-expansion, and Charpy impact) of the ferrite–pearlite wheel–disc steel and ferrite–bainite wheel-rim steel are studied. The designed steels are commercially available for realizing the goal of reducing automotive wheel weight.

* Corresponding authors. Tel.: +86 24 83680250; fax: +86 24 23906472 (J. Hu).
E-mail addresses: hujunral@163.com (J. Hu), dulx@ral.neu.edu.cn (L.-X. Du).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.07.036

2. Experimental details

2.1. Materials and thermomechanical processing condition

The tested steel was smelted by vacuum induction furnace, and cast into 150 kg ingots. The chemical composition is listed in Table 1. The ingots were forged into slabs. The 40 mm thick slabs were heated to 1200 °C, and held at that temperature for 1 h for the dissolution of microalloyed elements, then air-cooled to 920 °C. The slabs were then rolled into steel plates with 7 mm thickness after seven passes on the Φ450 mm trial rolling mill. The end temperature of finishing roll was controlled to 820 °C. Plate A was water-cooled at a cooling rates of 13 °C/s, and then coiled at 650 °C. Plate B was watercooled at a cooling rate of 30 °C/s, then coiled at 430 °C. Finally, the plates were cooled slowly to room temperature in an insulated blanket.

2.2. Mechanical properties testing

The tensile tests were conducted at room temperature using a Shimadzu AG-X universal testing machine according to ISO 6892-1: 2009 [16]. The steel sheets were cut into dog-bone shaped specimens (dimensions: 12.5 mm width, 50 mm gauge), and the crosshead speed was 3 mm/min. The bending and hole-expansion tests were conducted on a universal testing machine at room temperature according to ISO 7438: 2005 [17] and ISO 16630: 2009 [18], respectively. The parameters of the bending tests were as follows: specimens' length 180 mm, width 35 mm, bending speed 3 mm/min, bending radius T (thickness of sheet), and bending angle 180°. The parameters of the hole-expansion tests were as follows: specimens' thickness 3 mm, side length 100 mm × 100 mm, center aperture 16.5 mm, blank holder force 30 KN, punch velocity 6 mm/min, and control load 2.5 KN. The hole-expansion ratio was calculated as Eq. (1). The Charpy impact specimens were cut from the middle of the hot rolled steel perpendicularly to the rolling direction, and machined into Charpy V-notch specimens. The dimensions were 5 mm × 10 mm × 55 mm. The impact testing was conducted at 20 °C, 0 °C, −20 °C, −40 °C, −60 °C, −70 °C, respectively, on an Instron Dynatup 9200 series instrumented drop weight impact tester according to ISO 148: 1983 [19]. Additional −5 °C was added during the low temperature testing process in order to make up for the temperature rising. All of the tests were conducted three times at each parameter.

$$\text{hole expansion ratio} = (D_f - D_0)/D_0 \times 100\% \quad (1)$$

where D_0 is the initial punched-hole diameter and D_f is the final hole diameter after the test.

2.3. Microstructural characterization

Metallographic specimens were polished and etched with 4% nital before the investigation by means of a Leica DMIRM optical microscope (OM) and an FEI Quanta 600 scanning electron microscope (SEM). Transmission electron microscopy (TEM) studies were conducted on 3 mm diameter thin foils, which were electropolished using a solution of 8% perchloric acid alcohol, and examined by an FEI Tecnai G^2 F20 TEM at an accelerating voltage of 200 kV. The composition of the precipitate was investigated by energy–dispersive X-ray spectroscopy (EDX).

Table 1
Chemical composition range of the tested steel.

Elements	C	Si	Mn	P	S	Al	Nb + V + Ti	Fe
wt.%	0.09	0.17	1.50	0.007	0.0015	0.04	0.06–0.1	Bal.

2.4. Dynamic continuous cooling transformation diagram

Dynamic continuous cooling transformation (DCCT) diagram was determined using a thermomechanical simulator. Cylindrical specimens with $\Phi 6 \times 15$ mm were machined for dilatometer studies. The specimens were heated to 1200 °C, soaked for 180 s to dissolve microalloyed carbides, and then cooled to 820 °C. After held for 10 s, the specimens were compressed to a strain of 0.8 at a strain rate of 5 s^{-1}, and cooled to room temperature at the rate of 1–40 °C/s.

3. Results and discussion

3.1. Dynamic continuous cooling transformation

Fig. 1 shows the dynamic continuous cooling transformation diagram of the experimental steel. The transformation zone of ferrite (F) and pearlite (P) is ~550–750 °C. The transformation zone of bainite (B) is ~410–580 °C. The martensite can hardly generate at cooling rate lower than 40 °C/s due to the low carbon and microalloying design. The start cooling temperature is 820 °C, which is in the austenite single phase zone, thus, the microstructure is the pan-caked austenite due to heavy deformed in the austenite unrecrystallization zone. For the cooling procedure A, the ferrite first forms at continuous cooling rate of 13 °C/s and emit C to the surrounding austenite at the same time. The undercooled austenite is gradually C enriched, and then the pearlite forms at the subsequent slow coiling process of 650 °C. For the cooling procedure B, a small amount of ferrite and bainite successively form at the cooling rate of 30 °C/s, and then the rest undercooled austenite transforms to bainite at the coiling stage of 430 °C. Therefore, the tested steel has broad process window to produce the ferrite–pearlite steel or ferrite–bainite steel.

3.2. Microstructures characterization

Figs. 2 and 3 show the OM and SEM microstructures of the tested steels, subjected to the two cooling procedures, respectively. The microstructure of steel A consists of 90% coarse grained polygonal ferrite and 10% pearlite at a cooling rate of 13 °C/s and a coiling temperature of 650 °C, and the grain size of the polygonal ferrite is about 5 μm. The pearlite colonies are 5–8 μm, and distributed uniformly. The microstructure of steel B is composed of 20% fine grained polygonal ferrite and 80% bainite (granular bainite

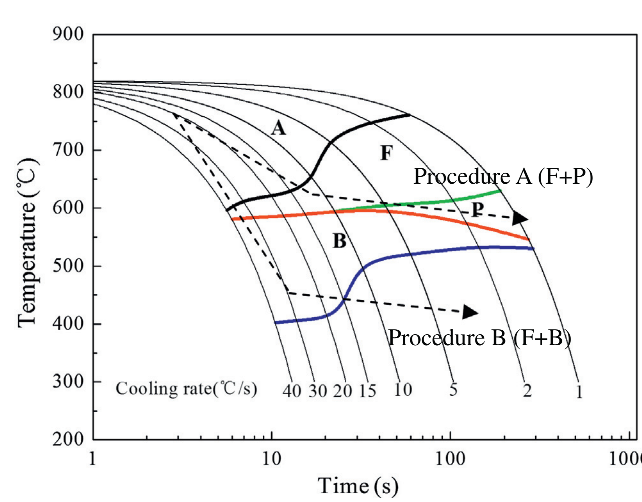

Fig. 1. Dynamic continuous cooling transformation diagram of tested steel.