Materials Characterization 118 (2016) 446–453

Contents lists available at ScienceDirect

Materials Characterization

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

On the determining role of acicular ferrite in V-N microalloyed steel in increasing strength-toughness combination

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ARTICLE INFO

Article history:
Received 25 January 2016
Received in revised form 19 June 2016
Accepted 20 June 2016
Available online 21 June 2016

Keywords:
V-N microalloying
Acicular ferrite
Intragranular nucleation
Toughness
Precipitates

ABSTRACT

Controlled rolling followed by accelerating cooling was adopted during industrial processing of a low-C V-N microalloyed steel. Furthermore, the effect of finish cooling temperature on the microstructure and mechanical properties was studied. The microstructure consisted of polygonal ferrite and coarse pearlite at finish cooling temperature of 660 °C, while fine pearlite was obtained instead of coarse pearlite at finish cooling temperature of 630 °C. With further decrease in finish cooling temperature to 570 °C, the microstructure comprised of fine polygonal ferrite, acicular ferrite, and a small amount of fine pearlite, such that high yield strength of 625 MPa and excellent impact toughness of 149 J at −60 °C was obtained. Acicular ferrite characterized by fine non-parallel ferrite platelets and high degree of misorientation played a determining role in enhancing strength and toughness.

1. Introduction

Advanced medium and heavy steel plates with high strength and excellent low temperature toughness are preferred as structural materials for ship hull, bridges, building, pressure vessels, and offshore structures [1–5]. To obtain good toughness and weldability, carbon-content is generally reduced. The decrease in strength due to lower carbon-content is compensated by the addition of Si and Mn. Further increase in strength is acquired through precipitation hardening and refinement of grain size by microalloying with Nb, V, and Ti, individually or in combination. Moreover, Nb is added during controlled rolling to inhibit austenite recrystallization, and Ti is added to avoid extensive austenite grain coarsening during the welding process [6–9]. To enhance the homogeneity of Nb-Ti microalloyed steels through thickness, expensive microalloying elements, such as Ni, Cr, Mo, and Cu, are added [1–2]. Recently, the focus has been toward developing as-hot rolled steels to replace conventional quenched and tempered steels from the viewpoint of production cost, energy, and efficiency considerations. Quenched and tempered steels can be substituted by microalloyed steels with equivalent strength and toughness [7,10]. But during thermo-mechanically controlled processing (TMCP) of advanced medium and heavy steel plates, deformation and cooling are rarely uniform across the thickness, because of which unfavorable microstructures such as coarse granular bainite and Widmanstatten ferrite are obtained at small reduction and low cooling rate in the center of the steel plate, and toughness is severely deteriorated [1,11].

Acicular ferrite is of considerable practical significance in the case of plates because it is characterized by relatively high strength and toughness [12]. In the early 1970s, acicular ferrite was preferred in high-strength low-alloy steel plates [13]. Acicular ferrite is the term used to describe a microstructure comprising of interlocking ferrite laths or plates with high density of crystallographic discontinuity [14], and the plates have fine-structure because of relatively low transformation temperature that is similar to bainite (~400–600 °C), and with similar transformation mechanism [15–16]. Acicular ferrite is considered a desirable microstructure in low carbon steel weldments because it provides superior toughness compared to other transformation products, such as conventional bainite, which is nucleated at the austenite grain boundaries and consists of parallel plates with similar crystallographic orientation [14]. Crack propagation in acicular ferrite is forced to adopt a tortuous paths, leading to better toughness [17]. Acicular ferrite is intragranularly nucleated transformation product, and the transformation starts with nucleation of primary plates at non-metallic particles and progresses to the second stage with the formation of a new generation of ferrite plates nucleated at the austenite/primary-plate interface by sympathetic nucleation mechanism [14,18–19]. Currently, there is continued interest to develop TMCP low carbon microalloyed steels with acicular ferrite microstructure because of high strength-high toughness combination [15,20–23]. The mechanism of inclusion stimulated nucleation is summarized as follows [18,24]: (1) solute depletion from austenite in the vicinity of non-metallic inclusion; (2) good lattice matching

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http://dx.doi.org/10.1016/j.matchar.2016.06.027

reduces interfacial energy between ferrite and inclusions; (3) thermal strain energy associated with different expansion coefficient of inclusion and matrix; and (4) availability of an inert surface for reduction in activation energy. The inclusions that are effective for nucleation site of acicular ferrite are Ti_2O_3, MnS + V (C,N), and MnS + CuS [24–26]. In the absence of sulfide inclusions, acicular ferrite is capable of nucleating on V(C,N) precipitates in V-N microalloying low S steel [12,27–28]. Ferrite exhibits Baker-Nutting orientation relationship with respect to small vanadium nitride (VN), and $(001)_{VN}//(001)_{\alpha}$ and $[110]_{VN}//[010]_{\alpha}$ [29]. In the habit plane of ferrite nucleated on $(110)_{VN}$, the lattice mismatch is extremely small: $[d_{VN(011)} - d_{\alpha(010)}] / d_{VN(011)} = (0.2927–0.2866) / 0.2927 = 0.021$, whereas perpendicular to the habit plane, the lattice mismatch is relative large: $[d_{VN(002)} - d_{\alpha(001)}] / d_{VN(002)} = (0.4139 / 2–0.2866) / (0.4139/2) = 0.385$ [24,29–30]. Therefore, acicular ferrite prefers to nucleate on the plane of $(110)_{VN}$ because of smaller lattice mismatch.

The objective of the present study is to explore the optimal finish cooling temperature for obtaining acicular ferrite across the thickness of V-N microalloyed medium heavy steel plate. The microstructural evolution, precipitation behavior, dislocation pattern, and crystallographic characteristics were studied. Moreover, the strengthening and toughening mechanisms are discussed. The formation of acicular ferrite played a determining role in enhancing strength and toughness.

2. Experimental

The melting, casting, and TMCP of experimental steel was conducted in a steel mill (Hebei Iron & Steel Group Company). The nominal chemical composition of the steel in weight % was 0.08–0.12C, 0.3Si, 1.5–1.8Mn, 0.01P, 0.005S, 0.02Al, 0.05–0.1V, 0.005–0.015Ti, 0.015–0.018N, and balance Fe. The 220 mm thick continuously cast slab was heated to 1250 °C for 3 h. The slab was subjected to two stage controlled rolling. In the first stage, the slab was rolled to an intermediate thickness of 90 mm via 6 passes. In the second stage, after air-cooling to 865–885 °C, the intermediate slab was rolled to 30 mm thick plates via 6 passes, and the finish temperature was controlled at 800–815 °C. The controlled rolling temperature was measured by Raytek non-contact infrared thermometers. The start temperature of accelerated cooling was 786–802 °C. Subsequently, the plate was accelerated cooled to finish temperature of 660 °C (steel A), 630 °C (steel B), and 570 °C (steel C), respectively, at accelerated cooling rate of 6.3 °C/s, 7.5 °C/s, and 9.0 °C/s. Next, the plates were air-cooled to room temperature.

The tensile tests were conducted at room temperature according to ISO 6892-1: 2009. The steel sheets were cut into dog-bone shaped specimens (dimensions: length 155 mm, width 25 mm, and thick 30 mm). Charpy v-notch impact tests were performed at −20 °C, −40 °C, −60 °C, respectively, using standard specimens (dimensions: $10 \times 10 \times 55$ mm^3) with a v-notch parallel to the rolling direction, consistent with ASTM E23 specification. The strength and toughness data presented is an average of at least three measurements.

The specimens for microstructural studies were polished using standard metallographic procedure and etched with a 4 vol% nital solution and observed using a Leica DMIRM optical microscope (OM) and Zeiss Ultra 55 scanning electron microscope (SEM). Using the linear intercept method, the grain size was determined by calculating the diameter of more than 50 grains. For electron back-scattered diffraction (EBSD)

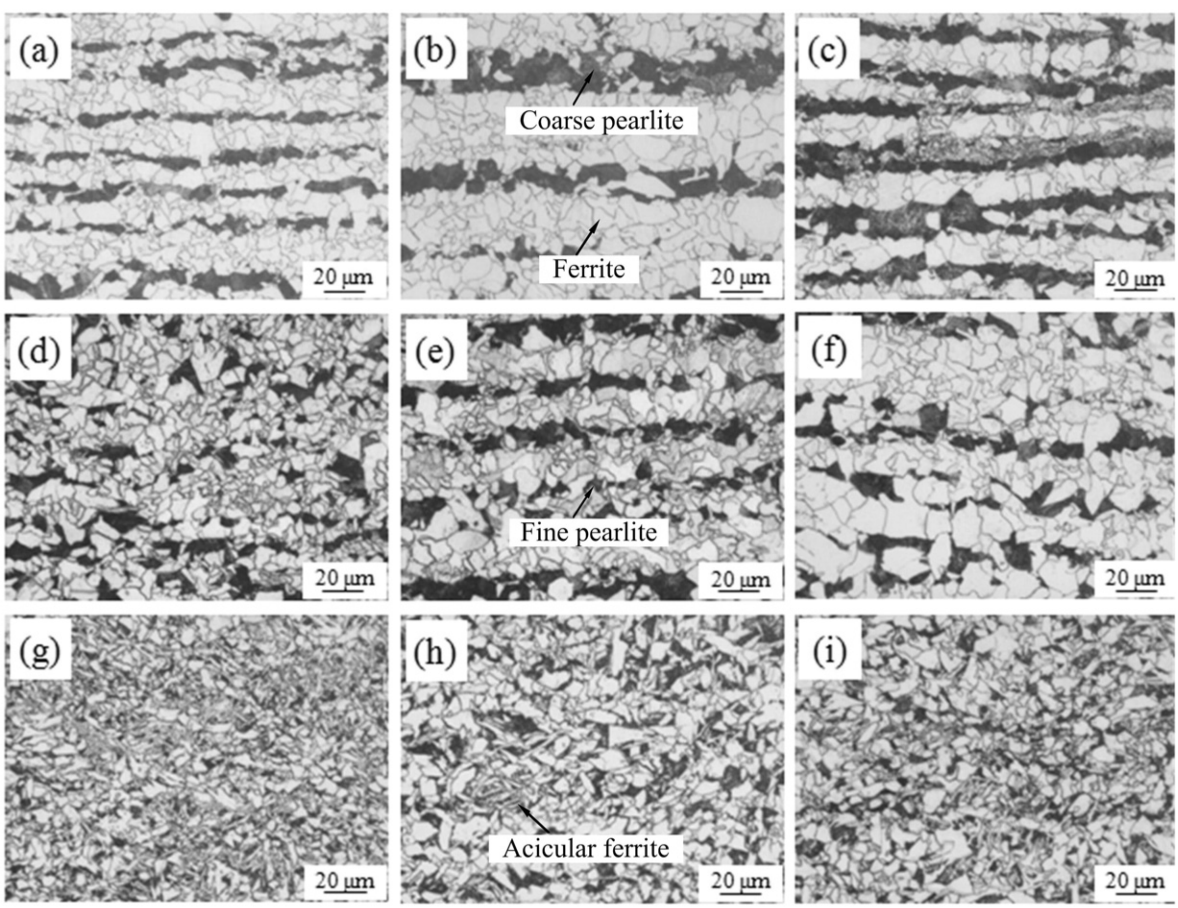

Fig. 1. Optical micrographs of experimental steels at different thickness and subjected to different finish cooling temperatures: (a) 1/8 thickness of steel A; (b) 1/4 thickness of steel A; (c) 1/2 thickness of steel A; (d) 1/8 thickness of steel B; (e) 1/4 thickness of steel B; (f) 1/2 thickness of steel B; (g) 1/8 thickness of steel C; (h) 1/4 thickness of steel C; and (i) 1/2 thickness of steel C.