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Microstructure and mechanical properties of TMCP heavy plate microalloyed steel

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ABSTRACT

A microalloyed steel heavy plate was subjected to two-stage controlled rolling and two-stage continuous cooling to explore the microstructure and mechanical properties in the plate. The objective was to obtain superior mechanical properties in the plate by exploiting the advantage of microalloyed precipitates in stimulating intragranular ferrite nucleation. Yield strength, tensile strength, and percentage of elongation of 550 MPa, 655 MPa, and 26.5% were obtained at quarter-thickness and 515 MPa, 645 MPa, and 29.5% at mid-thickness. The impact energy determined at −40 °C was ~93 J and 71 J for quarter-thickness and mid-thickness regions, respectively. The microstructure consisted of polygonal ferrite, acicular ferrite, and pearlite. Microalloyed precipitates provided effective nucleation sites for intragranular ferrite and ensured near-homogenous microstructure and mechanical properties in the heavy steel plate.

1. Introduction

Advanced heavy steel plates with high strength, improved low-temperature toughness, and excellent weldability combination are preferred as constructural materials for ship hull, bridges, buildings, pressure vessels, and offshore structures [1–5]. In regard to the alloy design of heavy steel plates, low-carbon design is preferred because of excellent low-temperature impact toughness and good weldability. Moreover, Nb is added for controlled rolling with the aim to inhibit austenite recrystallization, and Ti is added to avoid extensive austenitic grain coarsening during the welding process. To enhance the homogeneity of Nb–Ti microalloyed steels throughout the thickness, expensive microalloying, such as Ni, Cr, Mo, and Cu, are added. Although satisfactory strength–toughness combination is obtained in TMCP (thermo-mechanically controlled processing) and Q&T (quenching-tempered) Nb–Ti microalloyed steels, weldability is not satisfactory because of enhanced carbon equivalent caused by the addition of a large amount of microalloying elements, such as Ni, Cr, Mo, and Cu [1–6]. In TMCP of advanced heavy steel plates, the deformation and cooling are rarely uniform over the entire thickness, because of which inhomogeneous microstructure and mechanical properties are obtained in the plate. Thus, the low temperature rolling technology and novel Super-OLAC (on-line accelerated cooling) processes are adopted [5,7–8]. However, difficulties exist with thick steel plates. A large amount of Ni, Cr, Mo, and Cu increases the hardenability of austenite, and unfavorable microstructures such as coarse granular bainite and Widmanstatten are generated at small reductions and low cooling rate in the center of the heavy steel plate.

Literature suggests that vanadium carbonitrides V(C, N) can potentially provide sites for nucleation of ferrite. The small lattice mismatch between vanadium nitride (VN) (lattice parameters = 0.4139 nm) and ferrite (lattice parameters = 0.2865 nm) facilitates ferrite nucleation [9–12]. In laboratory melted V–N steel containing high S (~370–600 ppm), VN nucleates on manganese sulfide (MnS) inclusion forming a core-shell structure. These MnS + VN complex inclusions subsequently provide preferential sites for intragranular nucleation of ferrite [13–15]. However, it is difficult to control the size and distribution of MnS inclusions in a continuously cast slab. Large-size MnS promote cleavage crack.

It was recently stated that VN precipitates in austenite can stimulate intragranular nucleation of acicular ferrite and polygonal ferrite without the assistance of MnS inclusions in low-carbon V–N microalloyed and low-S steel [16–18]. Excellent mechanical properties (strength, ductility, and toughness) were obtained in the 20 mm medium-thick gauge plate subjected to low reduction and relatively lower accelerated cooling rate [19]. Furthermore, when the welding parameters were appropriate, low-temperature impact

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toughness was good both in the single-pass welding coarse-grained heat affected zone and in the multi-pass welding intercritically reheated coarse grained heat-affected zone [20,21]. Thus, based on the recently documented observations, we can take advantage of VN precipitates to stimulate the intragranular ferrite nucleation and thereby improve the homogeneity of the microstructure and mechanical properties in heavy plates. Moreover, acicular ferrite consists of interwoven ferrite laths or plates and this fine interlocking structure is preferred in low carbon HSLA steels because of high strength–toughness combination [22]. The generation of acicular ferrite throughout the thickness in place of coarse granular bainite and Widmanstatten is expected to improve the overall mechanical properties of heavy steel plates.

The objective of the present study is to take advantage of microalloying precipitates, in the present case, VN, to stimulate nucleation of intragranular ferrite in the absence of MnS inclusions. Excellent mechanical properties (strength, toughness, and ductility) and desired microstructure were obtained via two-stage controlled rolling and two-stage continuous cooling.

2. Experimental

2.1. Materials and thermo-mechanical processing

The experimental steel was melted in vacuum induction furnace and cast as 150 kg ingot. The chemical composition of the steel in weight percent was 0.08–0.14C, 0.2Si, 1.4–1.6 Mn, 0.0015S, 0.02–0.04Al, 0.06–0.12V, and 0.015–0.02N, balance Fe. The 150 mm thick slab was heated to 1200 °C for 3 h to dissolve the microalloying elements and rough rolled to 130 mm at 1150 °C. After air-cooling to 880 °C, followed by rolling using 4 passes with interpass time of 30 s on Φ450 mm trial rolling mill, the slab was rolled to a plate of 80 mm thickness. The finish rolling was controlled at 840 °C. After holding for 30 s, the plate was subjected to two-stage continuous cooling. In the first-stage, the plate was water-cooled at a rate of 5.8 °C/s to surface temperature of 450 °C and center temperature of 580 °C. Subsequently, the temperature was homogenized to 530 °C (self-tempering). In the second stage, the plate was air-cooled to room temperature at a cooling rate of ~0.125 °C/s.

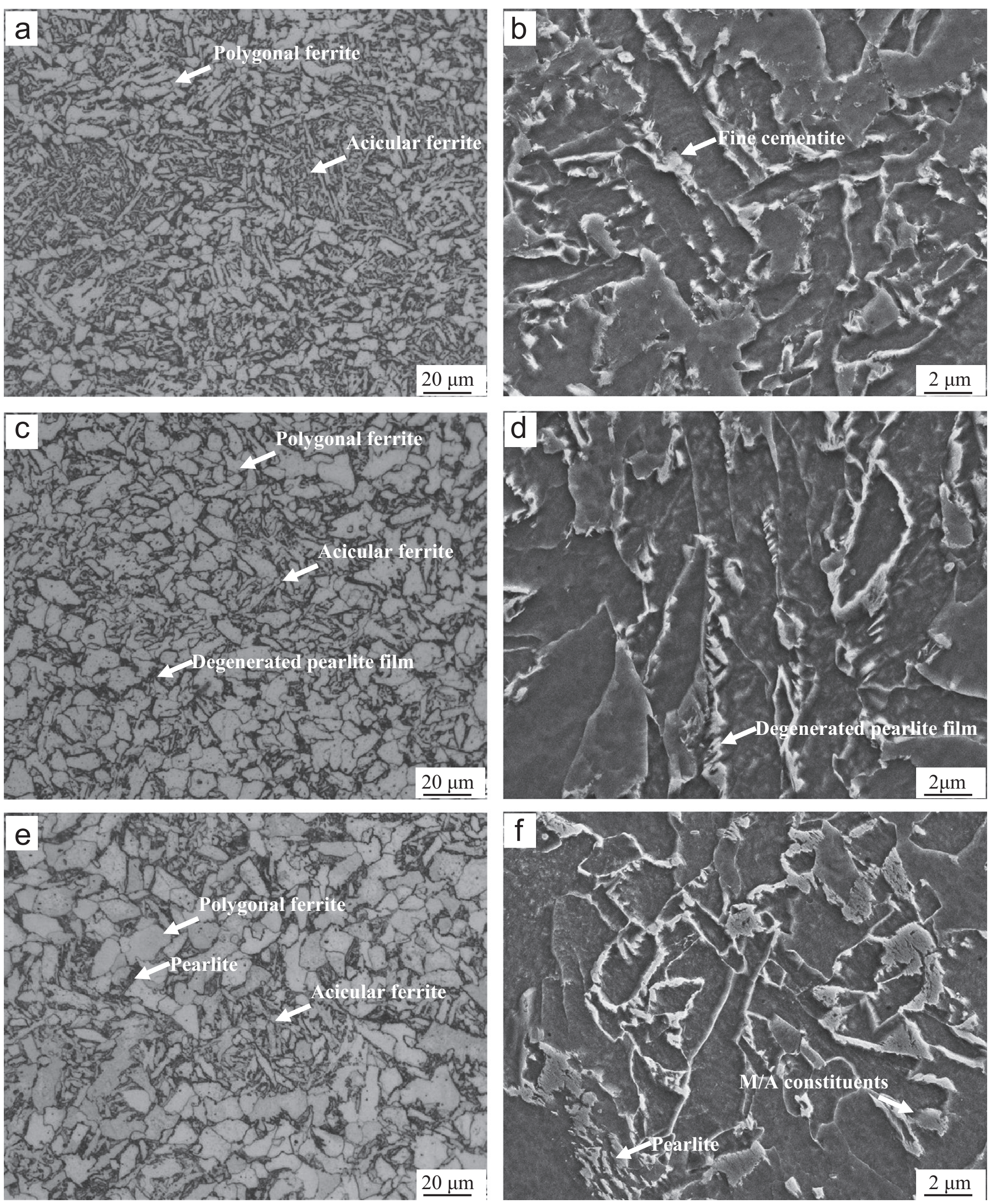

Fig. 1. Optical and SEM micrographs of experimental steel at different thicknesses: (a) OM of 1/8; (b) SEM of 1/8; (c) OM of 1/4; (d) SEM of 1/4; (e) OM of 1/2; and (f) SEM of 1/2.