Materials Science & Engineering A 626 (2015) 352–361

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Investigation on tempering of granular bainite in an offshore platform steel

Yanlei Zhou [a], Tao Jia [a], Xiangjun Zhang [a], Zhenyu Liu [a,*], R.D.K. Misra [b]

[a] The State Key Laboratory of Rolling and Automation, Northeastern University, P.O. Box 105, No. 11, Lane 3, Wenhua Road, HePing District, Shenyang 110819, People's Republic of China

[b] Department of Metallurgical and Materials Engineering, University of Texas at El Paso, 500 W. University Avenue, El Paso, TX 79968-0521, USA

ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form
17 December 2014
Accepted 18 December 2014
Available online 31 December 2014

Keywords:
Offshore platform steel
M-A constituent
Tempering
Low temperature toughness
Granular bainite

ABSTRACT

Granular bainite, where M-A constituents dispersed in bainitic ferrite matrix usually presents at the half thickness region in thermo-mechanically processed heavy gauge offshore platform steel. In the present work, the decomposition of M-A constituents during tempering at 600 °C was firstly revealed by transmission electron microscopy (TEM) analysis, which primarily involves the precipitation of cementite, recovery and recrystallization of highly dislocated ferrite matrix. Then, the effect of tempering on mechanical properties was investigated by tempering at different temperature for 60 min. Results indicated that, at tempering temperature of 500–600 °C, large quantity of micro-alloying carbides precipitated and partially compensated the loss of strength mainly due to the decomposition of M-A constituents. Compared with the as-rolled state, the decomposition of M-A constituents and softening of bainitic ferrite matrix after tempering have resulted in higher density of microvoids and substantial plastic deformation before impact failure.

1. Introduction

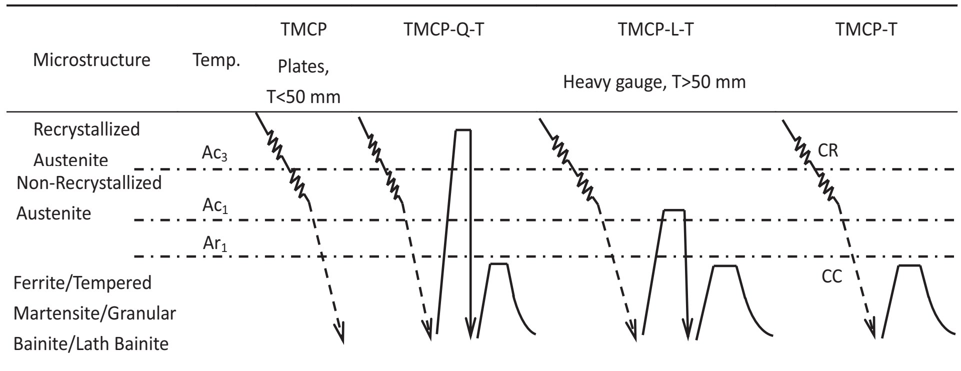
During the last decade, oil exploration is being extended to abyssal regions, leading to the increased size of offshore platform [1]. To this end, heavy gauge (> 50 mm) steel plates with yield strength exceeding 500 MPa are being increasingly needed to satisfy the requirement of safety and reliability [2–5]. In the thermo-mechanical controlled process (TMCP) of these high performance steel plates, the interior region, which experiences low total reduction ratio, low cooling rate and relatively high self-tempering temperature, is always the biggest concern. Microstructures with poor toughness, such as granular bainite (GB) would be present in that region [6]. Therefore, as illustrated in Table 1, different heat treatment processes, e.g. quenching and tempering (Q–T) [7] and lamellarizing and tempering (L–T) [8] are involved to achieve balanced combination of strength and toughness, and their uniformity through thickness direction. Compared with Q–T and L–T process, direct tempering after TMCP (TMCP-T) would be advantageous in production costs and efficiency. However, its feasibility requires further exploration.

Granular bainite was firstly revealed in early 1950s to be composed of 'coarse plates and those with an almost entirely granular aspect', together with islands of retained austenite and martensite, which are generally called M-A constituents afterward [9,10]. As one of the main constituent phases in steels, the formation mechanism and mechanical properties of granular bainite have been well discussed. For example, in a 0.08%C–1.75%Mn–0.40%Si–0.25%Mo–0.05%Nb steel, Mazancová and Mazanec [11] found that the M-A constituents in granular bainite primarily existed in blocky-shape while occasionally in rod-form. Twinned martensite is present in M-A constituent which has a carbon content of 0.60 wt%. The M-A constituents contribute significantly to tensile strength, but have a weaker influence of yield strength. The adverse effect of M-A constituents on impact toughness was carefully analyzed by Davis and King [12,13], and they concluded that the stress concentration due to residual transformation-induced stress field between M-A constituents and surrounding matrix resulted in deteriorated toughness. Zhang et al. [14] studied the tempering behavior of granular bainite in a 0.1%C–1.9%Mn–0.8%Si–0.5%Cr steel. Very little change can be noticed in the M-A constituents and ferrite matrix after tempered at 350 °C. For higher tempering temperature such as 620 °C, carbides precipitation and spheroidization in M-A constituents, recovery and recrystallization in bainitic ferrite matrix were observed. These processes involved have led to the increased impact toughness and, at the same time, the decreased tensile strength. However, in an ultralow carbon bainitic steels containing 0.053 wt% Nb, a prominent hardening effect was produced when tempering in

* Corresponding author. Tel.: +86 24 8368 0571.
E-mail address: zyliu@mail.neu.edu.cn (Z. Liu).

http://dx.doi.org/10.1016/j.msea.2014.12.074
0921-5093/

Table 1
Schematic diagrams of different processes for offshore platform steel with different gauges.



Temp.: temperature, CR: controlled rolling, CC: controlled cooling.

Table 2
Chemical compositions of the investigated steel (wt%).

C	Si	Mn	P	S	Al	Cr	Ni	Cu	Nb	Ti	N
0.08	0.10	1.69	0.0038	0.0014	0.025	0.31	1.18	0.50	0.049	0.012	0.0045

the vicinity of 600 °C owing to the precipitation of NbC in bainitic ferrite matrix [15].

In this work, tempering of granular bainite in a high performance offshore platform steel was investigated in detail. Characteristic changes of M-A constituents during tempering were captured by using scanning electron microscopy (SEM), electron probe micro-analyzer (EPMA) and TEM. Tempering at different temperatures was conducted to study the correlation between microstructure and mechanical properties, especially the low temperature toughness.

2. Experimental

As listed in Table 2, the experimental steel contains nickel for toughness, chromium and copper for corrosion resistance, and micro-alloying elements (niobium and titanium) for grain refinement and precipitation strengthening. Ingots were heated and forged into 115 mm × 120 mm × 200 mm slab. After homogenized at 1200 °C for 120 min, the slab was hot rolled with a two-high 450 mm experimental rolling mill. The thickness of slab was reduced from 115 mm to 27 mm by 7 passes with an average reduction ratio of 20% per pass. Right after the finish rolling, accelerated cooling was initiated at 810 °C and ended at 500 °C with an average rate of 11 $°C\,s^{-1}$. Finally, the steel plates were air cooled to room temperature. To investigate the decomposition kinetics of M-A constituents, a thermal–mechanical simulation test was carried out with the sample size of ⌀8 mm × 15 mm. The sample was firstly heated at a rate of 1 $°C\,s^{-1}$ to 600 °C, and then hold for 15, 30, 60 and 120 min respectively before air-cooled to room temperature. Using a resistance heated furnace, the effect of tempering temperature on mechanical properties was studied by tempering at 300, 400, 500, and 600 °C for 60 min, respectively. The tempering time started from the loading of samples into the furnace. To evaluate the tensile properties and impact toughness, large sample size (100 mm × 130 mm × 27 mm) was employed. Tensile and Charpy V-Notch (CVN) impact test samples were prepared along the rolling direction at half thickness region. The tensile samples (⌀8 mm, parallel length of 50 mm) were tested at room temperature using an Instron tensile testing machine at a crosshead speed of 5 $mm\,min^{-1}$. The CVN samples (10 mm × 10 mm × 55 mm) were prepared with the notch parallel to the thickness direction. The CVN impact tests were conducted at −40 °C and −60 °C using an Instron Dynatup 9200 series instrumented drop weight impact tester.

Microstructure examination was made with EPMA (JEOL JXA-8530F) and TEM (FEI Tecnai G2 F20). Special attention was paid to the sample preparation for EPMA analysis. Firstly, samples (10 mm × 15 mm × 6 mm) were sectioned with the wire cut electrical discharge machining. After mounted in Bakelite, the sample were grinded with new 600–1500 grit SiC papers and then polished with synthetic diamond lapping paste (2.5 μm). Subsequently, 5 min ultrasonic cleaning in ethanol and air-drying at room temperature were carried out to remove any residue on the surface [16]. Finally, the sample was etched in 4% nital solution for 8 s and another ultrasonic cleaning was performed. The sample was analyzed at an acceleration voltage of 20 kV, beam current of 1.97×10^{-8} A and counting time of 500 ms. A superior vacuum condition, i.e. 10^{-8} Pa was achieved by reserving the samples inside the chamber for more than 12 h [17]. In this work, line scanning (counts versus distance curves) were employed to qualitatively study the carbon distribution in M-A constituents during tempering. For the TEM samples, square slices with the thickness of 400 μm were cut from samples and then mechanically grinded below 50 μm with 600–1500 grit SiC paper. Then, ⌀3 mm discs were punched and electro-polished to perforation in a mixture of 9% perchloric acid and 91% absolute ethyl alcohol at −40 °C and the potential of 30 V.

3. Results

3.1. Decomposition of M-A constituent

Fig. 1 shows the TEM image of samples tempered at 600 °C for different time. Two types of M-A constituents embedded in bainitic ferrite matrix are identified in the as-rolled sample (see Fig. 1a). The first one contains high density of dislocation (marked as 1), while the other is characterized by twinned martensite (marked as A) which is confirmed by the selected area diffraction