Materials Science & Engineering A 607 (2014) 559–568

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Effect of heat-treatment on-line process temperature on the microstructure and tensile properties of a low carbon Nb-microalloyed steel

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ARTICLE INFO

Article history:
Received 16 January 2014
Received in revised form
31 March 2014
Accepted 4 April 2014
Available online 13 April 2014

Keywords:
Microalloyed steel
Tensile properties
EBSD
Precipitation strengthening
M/A constituent
Strain hardening capacity

ABSTRACT

The microstructures of a low carbon Nb-microalloyed steel processed with the Heat-treatment On-line Process (HOP) technology, whose highest heating temperature ranges from 560 °C to 720 °C, were characterized. The tensile properties were evaluated from the ThermoMechanical Control Process (TMCP) treated samples. The results indicate that the microstructure is primarily composed of non-equiaxed ferrite grains with martensite/austenite (M/A) constituent dispersed at grain boundaries for the specimens with different HOP temperature. The refinement of niobium precipitate particle and increase of volume fraction of precipitation could induce the enhancement of the yield strength when increasing the HOP temperature. The relationship between the average size and volume fraction of the precipitate particles and the precipitation strengthening part of yield strength follows the Orowan–Ashby equation. Moreover, the yield ratio slightly reduces with the increasing amount of M/A constituent, and a platform of yield ratio emerges when the HOP temperature ranges from 590 °C to 720 °C.

1. Introduction

The material of High Strength Low Alloy (HSLA) bridge steels requires high strength, high toughness and superior weldability. The current demand is the application of structural material in permafrost ground and seismic regions where the steels will be subject to large strain caused by seismic activity or frost heave, so in addition to the above mentioned properties, the steels should have high deformability to guarantee the safety.

The deformability can be improved by increasing the strain hardenability of the steel. In this case the high deformability is characterized by low yield ratio of the yield strength and tensile strength, high work hardening exponent (*n*-values) and continuous yield behavior [1]. Studies have shown that the strain hardening capacity is intimately associated with the microstructure of the steel. The target microstructure yields a combination of high strength, high toughness and excellent strain hardenability [2,3]. It can be obtained by optimizing the chemical composition and the ThermoMechanical Control Processing (TMCP) schedule.

A lot of researches have been executed since low carbon HSLA steels with acicular ferrite (AF) microstructure were developed [4–9]. The AF microstructure, which has been considered to have the optimum mechanical properties, was complex consisting of quasi-polygonal ferrite (QF), granular bainitic ferrite (GF) and a little banite ferrite (BF) with dispersed islands of secondary phases (mainly martensite/austenite constituent) in the ferrite matrix [10–12]. According to the micromechanics model of dual-phase microstructure [14], the dual-phase microstructure composed of the soft matrix phase and the hard secondary phase brought high strain hardenability [3,13], and the strain hardening capacity increased as the strength difference between the matrix phase and secondary phase increased together with the increasing fraction of hard secondary phase. In addition, microalloy element Nb could strengthen matrix by forming nano-sized carbide precipitates during the TMCP [15–17]. These precipitates can restrain the recovery of the dislocations by pinning effect, and significantly improve the yield strength of the steel, which were considered to be able to affect the strain hardening capacity, either.

To obtain the optimum microstructure with high strength and deformability, dual-phase or multi-phase, JFE Steel developed the Heat-treatment On-line Process (HOP) directly applied after the Accelerated Cooling (ACC) during the TMCP [18]. The study of this paper aims at investigating the relationship between the microstructure and the tensile properties of the test steel with varying HOP temperature. To reach this goal, the microstructure and precipitation behavior of the test steel were characterized to correlate with the strength and strain hardening capacity.

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http://dx.doi.org/10.1016/j.msea.2014.04.027
0921-5093/

2. Experimental material and procedures

The steel used in this work was a commercial HSLA steel. Its chemical composition is listed in Table 1.

The round bar specimens with a length of 75 mm and diameter 15 mm for compressive deformation were cut from the steel plate. The simulated TMCP was conducted in a Gleeble 3500 system, the schedules of which were given in Fig. 1. Once reheated at 1180 °C during 10 min, all deformation schedules are applied: a simulated "roughing" step performed at a temperature of 1080 °C using a compression of 35% in the γ recrystallization region (schedule A) and an additional "finishing" step performed at a temperature of 820 °C (schedule B), which was situated in the non-recrystallization region, using a compression of 30%. Accelerated Cooling (ACC) started at 780 °C with a 15 °C/s cooling rate and was interrupted at 560 °C. HOP, whose highest heating temperature ranges from 560 °C to 720 °C, was conducted immediately after the interruption of ACC with a 2 °C/s heating rate and followed by the simulated air cooling.

After the simulation process, samples for metallographic observation were cut on the plane perpendicular to the axis of compression, and carefully prepared according to the standard method. For examination of the microstructure by Optical Microscopy (OM), a 4% nital solution was used. To observe the M/A constituent, the Lepera's reagent of 1 g sodium metabisulfite in 100 ml distilled water mixed with 4 g of picric acid dissolved in 100 ml of alcohol was used. By this way, M/A constituent (white) and ferrite (gray phase) can be identified totally by OM. Measurements of size and area fraction of M/A constituent were performed mainly by using of image analysis with the software Image-Pro Plus. For each specimen, at least 5 fields of view containing at least 500 particles were measured at a magnification of 1000×. Thin foils for transmission electron microscopy were prepared using the twin-jet method and observed in a JEM-2010 high-resolution transmission electron microscope (TEM). Quantitative measurements of precipitate particles were carried out by using of image analysis on TEM image. The average size and fraction of precipitate particles were statistically measured by averaging at least 1000 particles and 5 fields of view containing at least 500 particles from the images of TEM, respectively. Electron back scattered diffraction (EBSD) examinations were performed on a Hitachi S-3400 Scanning Electron Microscope (SEM) equipped with a TSL EBSD system. The EBSD scan was carried out with step size of 0.25 μm, and the EBSD effective grain size was calculated as the equivalent circle diameter related to the individual grain area.

Table 1
Chemical compositions of the test steel (wt%).

C	Si	Mn	P	S	Mo+Ni+Cu	Nb+Ti+V
0.056	0.15	1.70	0.005	0.002	≤0.70	≤0.06

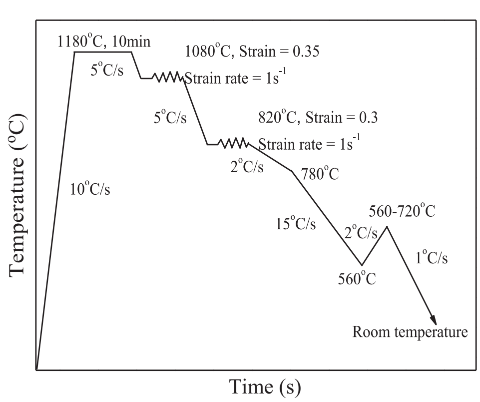

Fig. 1. Graph of the simulated TMCP on the Gleeble for the steel with different HOP temperature after hot deformation. HOP—Heat-treatment On-line Process.

The micro-tensile test [19,20] specimens were wire-cut according to Fig. 2 from the TMCP treated samples and tensile tested on a Inspekt Table tensile testing machine at room temperature with a cross-head speed of 0.25 mm min^{-1}. To keep the steady tensile deformation of the specimen, a customed fixture has been designed for the micro-tensile test, as shown in Fig. 3a and b. The observations of the tensile sample before and after the tensile test, shown in Fig. 3c and d, respectively, revealed that the specimen broke within the gauge length and there was no deformation of the specimen shoulder. For each simulated process, three tensile samples were tested, and the yield strength was determined by the 0.2% offset flow stress.

3. Experiment results

3.1. Tensile properties

The tensile properties of specimens varied with the highest HOP heating temperature and the typical stress–strain curves of the tensile tests are shown in Fig. 4a and b, respectively. It is indicated that the yield strength and the tensile strength all increase with the HOP temperature, whereas the Yield Ratio (YR), which equals to the ratio of yield strength and tensile strength, decreases slightly. The YR is a subordinate criterion for expression of strain hardening. A lower YR represents a better strain hardening capacity.

3.2. Microstructure

Optical and SEM micrographs of the specimens varied with the highest HOP heating temperature are shown in Fig. 5. The transformed microstructures of the specimens with different HOP temperatures all consist of non-equiaxed ferrite and secondary phases dispersed in the ferrite matrix. The secondary phases are present as black or gray islands and mostly distribute at the grain boundaries of ferrite. Based on the researches by Xiao et al. [10–12], this complicated intermediate transformation microstructure is defined as acicular ferrite (AF), which is complexly consisting of quasi-polygonal ferrite (QF) and granular bainitic ferrite (GF) with dispersed islands of secondary phases (mainly M/A constituent) in the ferrite matrix. The corresponding microstructure phases have been marked in the SEM micrographs of this study (Fig. 5).

Representative bright field TEM micrographs of the specimen with the HOP temperature of 560 °C and 720 °C are presented in Fig. 6a–d. In general, the microstructure is predominantly composed of non-equiaxed ferrite grains with martensite/austenite (M/A) islands at numerous grain boundaries based on TEM observations. It is revealed that M/A islands in the sample with higher HOP temperature (Fig. 6c and d) are much larger than in the sample with lower HOP temperature (Fig. 6a and b). Since M/A constituent is predominantly present as a secondary phase in the steel, a detailed TEM study has been carried out to understand its microstructure. Fig. 7a and b shows bright and dark field TEM micrographs of M/A constituent and the corresponding SAD pattern analysis is presented in Fig. 7c. The SAD pattern analysis indicates the presence of retained austenite together with martensite. In addition, a small fraction of degenerated pearlite also exists as a additional phase. Typical morphology of degenerated pearlite is shown in Fig. 7d.

Fig. 8 shows the morphology variation of M/A constituent with the HOP temperature. It can be seen that M/A constituent exists at