Materials Science & Engineering A 666 (2016) 214–224

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Effect of microstructure on the crack propagation behavior of microalloyed 560 MPa (X80) strip during ultra-fast cooling

J. Zhao [a], W. Hu [a], X. Wang [a,b], J. Kang [a], G. Yuan [a,*], H. Di [a], R.D.K. Misra [c]

[a] State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, China
[b] Shougang Qian'an Iron & Steel Co., Ltd., Qian'an 064404, China
[c] Laboratory for Excellence in Advanced Steel Research, Department of Metallurgical, Materials and Biomedical Engineering, University of Texas at El Paso, 500 W. University Avenue, El Paso 79912, USA

ARTICLE INFO

Article history:
Received 23 January 2016
Received in revised form
22 April 2016
Accepted 22 April 2016
Available online 23 April 2016

Keywords:
Ultra-fast cooling technology
X80 pipeline steel
Critical thickness
Acicular ferrite
DWTT

ABSTRACT

A novel thermo-mechanical controlled processing (TMCP) involving ultra-fast cooling (UFC) was used to process microalloyed 560 MPa (X80) strip with critical thickness of 22 mm. The microstructure and mechanical properties including tensile, Charpy v-notch impact toughness, and drop weight tear test (DWTT) properties were studied, with particular focus on the effect of microstructure on fracture and crack propagation behavior during DWTT test. The study underscores that the processed strip comprising of acicular ferrite (AF), bainitic ferrite (BF), together with finely distributed martensite/austenite (M/A) constituent provided excellent combination of strength, toughness and crack arrest property. The yield strength (618 MPa), tensile strength (752 MPa), and low-temperature toughness (upper shelf energy of 302 J, transition temperature of −74 °C) as well as DWTT shear area (100%) met the requirements of API SPEC 5L. The predominantly AF microstructure with small-size M/A constituent improved the low-temperature toughness by increasing the critical fracture stress and increased the ability to hinder crack propagation during Charpy test. The AF and finely distributed M/A constituent effectively deflected the crack propagation during DWTT indicating excellent crack arresting property of pipeline strip. It is the cooling schedule of UFC that was responsible for decreasing the effective grain size and increasing the mechanical properties.

1. Introduction

Pipeline steels are widely used to transport crude oil or natural gas at higher operating pressure, which require large diameter and thick pipes [1,2]. Thermo-mechanical controlled processing (TMCP) is widely adopted to process pipeline steels. The development of high strength pipeline steels facilitates increase in the thickness of pipeline to critical values of 25.4 mm and 22 mm with respect to X70 and X80 grade steels, respectively. However, there are problems in consistently obtaining mechanical properties by TMCP in pipeline strips, one of the major problems being the unstable shear properties in DWTT with increased thickness, which is a major obstacle in the exploitation of pipeline strips on a large scale [3,4].

Ultra-fast cooling (UFC) approach developed in our laboratory, and characterized by high cooling capability is now widely used to process microalloyed steels, including bearing steel, and bridge steel [5–7]. A trial was conducted to improve the stability of DWTT performance by varying the cooling schedule of TMCP using UFC [8], and X70 (25.4 mm) and X80 (22 mm) pipeline steels with excellent combination of strength, low-temperature toughness, and excellent DWTT ductile shear area were successfully processed using the novel TMCP.

In present study, X80 pipeline strip (22 mm) was industrially processed using novel TMCP involving UFC, and the relationship between UFC, microstructure, low temperature toughness, and crack arresting property was explored. The present study is aimed at illuminating toughening and crack arresting mechanisms in X80 strip with critical thickness processed by novel TMCP together with outlining the benefits of UFC.

2. Experimental procedure

2.1. Material and thermo-mechanical controlled processing

The experimental X80 pipeline strip with critical thickness of 22 mm was industrially processed on a hot strip mill equipped with ultra-fast cooling system (after finish rolling mill). The chemical composition of the strip is presented in Table 1.

---

* Corresponding author.
E-mail address: yuanguoenu@163.com (G. Yuan).

http://dx.doi.org/10.1016/j.msea.2016.04.073
0921-5093/

Table 1
Chemical composition of studied steel (wt%).

Element	C	Si	Mn	P	S	Nb+V+Ti	Cr+Mo	Cu+Ni
Content	0.061	0.11	1.75	0.0079	0.0014	0.094	0.49	0.30

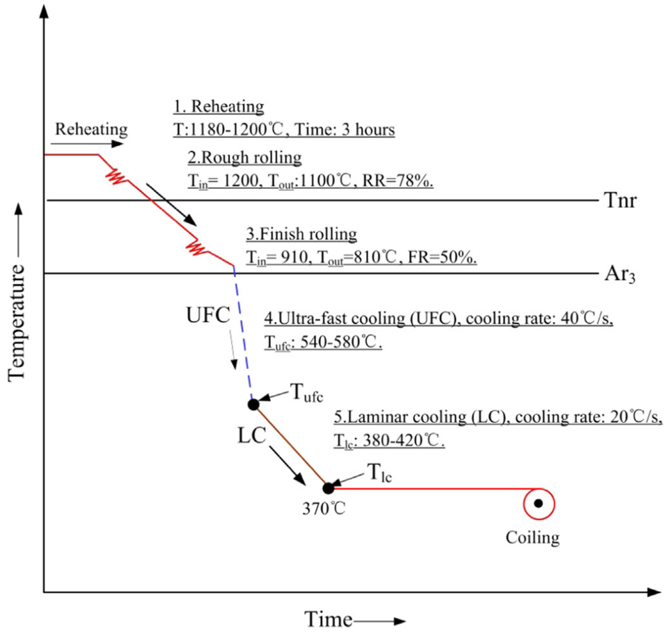

Fig. 1. Schematic diagram of TMCP involving UFC.

The slab with thickness of 200 mm was reheated to 1200 °C for 3 h to dissolve the microalloying elements. In the controlled rolling process, two steps of rolling, rough rolling and finish rolling, were performed in the temperature range of 1080–1000 °C and 910–810 °C, respectively, and the finish rolling temperature was 810 °C, which is above the critical transformation temperature of Ar_3 (the temperature of austenite to ferrite transformation). An overall grain refinement is expected, when we consider the deformation ratio of 78% during rough rolling and 50% during finish rolling. In the controlled cooling process, the cooling schedule of UFC combined with laminar cooling was applied to control the microstructure. The hot strip was first cooled to a temperature of 540–580 °C at a cooling rate of 40 °C/s via UFC, then cooled to the coiling temperature of 380–420 °C at a cooling rate of 20 °C/s by laminar cooling. A schematic diagram and rolling parameters of TMCP are presented in Fig. 1.

2.2. *Microstructural characterization*

The specimens used for microstructural observations were cut at quarter position of width. After mechanical polishing, the metallographic specimens cut from the longitudinal-normal (L-N) plane were etched with 4% nital and observed by Leica DMIRM optical microscope. Etchant consisting of 2% perchloric acid and alcohol was used for electron back-scattered diffraction (EBSD) analysis, and the EBSD analysis was carried out using a FEI Quanta 600 scanning electron microscope (SEM). For substructure observations, thin-foils of 40 μm thickness were prepared and twin-jet electropolished using solution of 8% perchloric acid and 92% ethanol at −30 °C. The foils were studied by a Tecnai G^2 F20 transition electron microscope (TEM). The fracture surface and crack propagation path were studied by SEM. Volume fraction of microstructural constituents was measured from OM micrographs using an image analyzer.

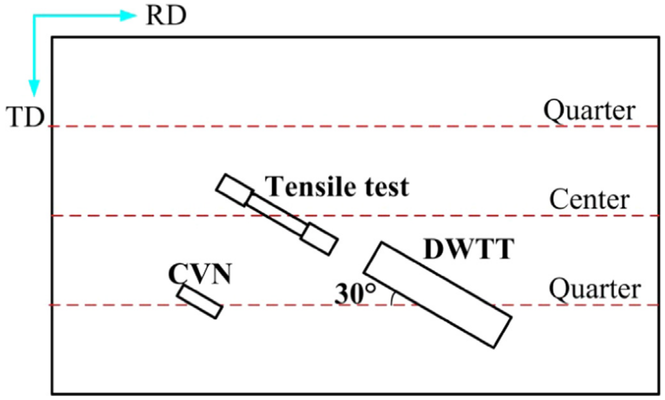

Fig. 2. Schematic diagram of sampling positions for Charpy impact and DWTT tests.

2.3. *Mechanical property tests*

The samples for tensile tests (12.7 mm in diameter and 50 mm in gage length) and for DWTT (305 mm × 76.2 mm × 22 mm) were machined in accordance with ASTM A370 and SY/T 6476 Chinese standards, respectively. Charpy samples were 10 mm × 10 m × 55 mm in size. Fig. 2 shows the sampling positions in the steel strip. Tensile tests were carried using a WDW-300 universal machine at a constant displacement rate of 3 mm/min. Charpy tests were carried using an instrumented impact tester in the temperature range of −120 and −20 °C at intervals of 20 °C. DWTT experiments were performed at −15 °C. The fracture surfaces of samples tested by Charpy tests and DWTT were studied by SEM. The crack propagation behavior beneath the fracture surface of DWTT samples was also studied by SEM after preserving the fracture surface by plating with nickel. Tensile properties of X80 pipeline strip and data of statistical relevance obtained using identical TMCP schedule, indicating the competitive combination of strength and ductility and excellent DWTT properties in terms of the API SPEC 5 L specification is shown in Fig. 3.

3. Results

3.1. *Microstructure*

The microstructure at mid-thickness is expected to consist of relatively coarser grains compared to the microstructure at the surface or quarter position because of relatively low cooling rate. Thus, the specimens used for microstructural analysis and subsequent tests, i.e. tensile tests and Charpy impact tests, were taken from the mid-thickness position. Fig. 4 is the optical micrograph of studied steel at mid-thickness. The microstructure predominantly consisted of acicular ferrite (AF), bainitic ferrite (BF) together with finely distributed martensite/austenite (M/A) constituent (indicated with arrow in Fig. 4). AF usually nucleates intragranularly in the deformed austenite, and the formation of AF needs sufficient deformation ratio in the non-recrystallization region and high cooling rate [9]. In contrast, BF nucleates at austenite boundaries and forms packets [10,11]. AF has arbitrary orientations, while BF has comparatively wider grains (indicated with arrow in Fig. 4(b)). The volume fraction of AF and BF were determined to be ~88% and ~12%, respectively. AF is beneficial in decreasing the effective grain size [1,12]. Given that the microstructure of AF and BF in the studied steel was complex, the effective grain size was determined via EBSD analysis. The secondary M/A constituent distributed in the BF matrix or between AF laths was fine with long-strips, and irregular as shown in Fig. 4(b). Fig. 5 is the TEM micrograph showing interwoven ferrite laths and small