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The relationship between microstructure, crystallographic orientation, and fracture behavior in a high strength ferrous alloy

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ABSTRACT

The study described here focuses on toughening and crack-arrest mechanism in a 560 MPa microalloyed pipeline strip steel processed by combination of thermo-mechanical controlled processing and ultra-fast cooling (TMCP-UFC) and compared with the strip processed at low cooling rate and high cooling interrupt temperature (TMCP-LC). Furthermore, delamination mechanisms involved in drop weight tear test (DWTT) were also studied from the perspective of microstructure, crystallographic orientation, and stress field ahead of the crack. The TMCP-UFC processed strip was primarily composed of acicular ferrite (AF), bainitic ferrite (BF), and small-sized martensite/austenite (M/A) constituent, and the microstructure was homogeneous across the thickness. While the TMCP-LC processed strip mainly consisted of quasi-polygonal ferrite (QPF), degenerate pearlite (DP), and small fraction of BF. The TMCP-UFC processed strip exhibited excellent low-temperature toughness with upper shelf energy (USE) of ~302 J and transition temperature (TT) of ~−75 °C in relation to TMCP-LC processed strip with USE of ~273 J and TT of ~−30 °C. Significant consumption of crack-propagation energy during ductile fracture and smaller effective grain size of ~2.4 μm were responsible for higher USE and lower TT of TMCP-UFC processed strip compared to TMCP-LC processed strip with effective grain size of ~4.0 μm. The smaller effective grain size with respect to TMCP-UFC processed strip contributed to excellent crack-arrest property by deflecting the propagated crack. In the TMPC-UFC processed strip, delamination occurred along the crystallographic cleavage plane of {001} under plane strain condition at mid-thickness. In contrast, besides delamination mechanism along the cleavage plane, delamination also occurred along the macro-segregation band under plane strain condition at mid-thickness in the TMCP-LC processed strip, which led to severe delamination.

1. Introduction

Excellent low-temperature toughness and crack-arrest property of pipeline steel are significant for the development of high-grade and thick pipeline steels. To develop ultra-high strength steels or thicker pipeline steel with excellent toughness and crack-arrest performance, it is important to focus on fundamental toughening and crack-arresting mechanisms.

Thermo-mechanical controlled processing (TMCP) is widely used to produce X80 pipeline steel. Previous studies have indicated that the low-temperature toughness and crack-arrest property are closely related to microstructural constituents of pipeline steels [1–7]. For X80 pipeline steel, ideal microstructure mainly consists of acicular ferrite (AF) together with refined martensite/austenite (M/A) constituent. The AF phase is the desired microstructure, and is beneficial to toughness because of smaller effective grain size compared to other phases, i.e. polygonal ferrite, quasi-polygonal ferrite, and granular bainite etc. [2–4]. AF can improve low-temperature toughness (including upper-shelf energy (USE) and energy transition temperature (ETT)) and crack-arrest property by deflecting the crack and increasing consumption of crack propagating energy during fracture [5–7]. Hence, controlled rolling process together with accelerated cooling are usually adopted during TMCP to improve low-temperature toughness of pipeline steel by promoting transformation of AF [5,8,9]. Additionally,

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crystallographic orientation also has significant influence on toughness and fracture behavior of pipeline steel [10–16]. The {001} crystallographic plane associated with the fracture mode is cleavage plane during fracture of cubic material, and fracture can easily occur along the cleavage plane with relative low energy consumption. The volume fraction of {001} cleavage plane is closely related to fracture mode and toughness of material during fracture. When texture components involving {001}, i.e. {001}[100](cube), {001}[110](rotated cube), are predominantly present in steel, delamination can occur during ductile fracture on the fractured surface, which further deteriorates the toughness of steel [10,14].

Ultra-fast cooling technology (UFC) developed in our laboratory was used to process large-thick pipeline strip. The drop-weight tear test (DWTT) performance of the processed pipeline strip was significantly improved, in relation to strip processed by conventional TMCP [17,18]. To study toughening and crack-arresting mechanisms involved in UFC-produced pipeline strip, studies were carried out from the viewpoint of microstructure and crystallographic orientation. The objective of the work described here is to focus on toughening and crack-arrest mechanisms from the perspective of microstructure, together with the delamination mechanism. It is expected that the study will provide a theoretical basis to develop high strength pipeline steels with excellent toughness and crack-arrest performance.

2. Materials and experimental procedure

2.1. Materials and thermo-mechanical controlled processing

The chemical composition of the microalloyed 560 MPa (X80) pipeline steel studied here is presented in Table 1. The studied X80 pipeline strip was industrially processed on a hot strip mill equipped with ultra-fast cooling system (after finish rolling mill). To study the influence of microstructure on the fracture behavior of pipeline strip, different microstructural constituents were obtained by using identical controlled rolling schedules but different controlled cooling schedules during TMCP. Slabs of thickness ~200 mm were first reheated to 1200 °C for 3 h to dissolve the microalloying elements. In the controlled rolling process, two steps of rolling (rolling in the recrystallization region and non-recrystallization region, respectively) were performed in the temperature range of 1200–1100 °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). Grain refinement effect was expected by rolling with deformation ratio of 78% in the recrystallization region and 50% in the non-recrystallization region. In controlled cooling process, two different cooling schedules first cooled 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, referred as TMCP-UFC. Another cooling schedule referred as TMCP-LC with lower cooling rate of 20 °C/s and relative higher cooling interrupt temperature of 590–610 °C was also adopted for comparison with TMCP-UFC. The schematic diagram of TMCP and corresponding parameters are presented in Fig. 1.

2.2. Microstructure characterization

Cross-sections consisting of longitudinal and short transverse directions were cut for microstructural observations. Specimens were mechanically polished and etched with 4% nital solution for 20 s, 10 s, and electrolytically polished with 30% perchloric acid solution for 20 s for scanning electron microscopy (SEM) (ULTRA 55, Zeiss, resolution:1.0 nm), field emission electron probe analysis (JEOL JXA-8530F, resolution: >0.1 μm), and electron back-scattered diffraction (EBSD) (resolution 1.0 nm) studies, respectively. Thin foils of dimensionsφ3 mm × 40 μm were studied by transmission electron microscopy (TEM) (Tecnai G2 F20, FEI, resolution: 0.24 nm) after jet polishing in 10% perchloric acid for 30 s. Given that the cooling rate at mid-thickness of pipeline strip of thickness 22 mm was lower compared with quarter and surface positions, the microstructure at the mid-thickness was coarser. Thus, EBSD analysis and TEM observations were carried out at mid-thickness. Given that elemental segregation was expected to occur at mid-thickness, electron probe analysis was carried out at mid-thickness. Macro-texture of pipeline strips were studied at mid-thickness by X-ray diffraction equipment (D8 DISCOVER, AXS, minimum step: 0.0001°) using specimens of dimensions 20 mm × 20 mm × 4 mm.

2.3. Mechanical property tests

Specimens for Charpy-v notch impact test (CVN, dimensions of 10 mm × 10 mm × 55 mm) and drop-weight tear test (DWTT) (dimensions of 72 mm × 350 mm × whole thickness) were cut from the studied strips and are schematically illustrated in Fig. 2. Charpy impact test and drop-weight tear test (DWTT) were carried out using instrumented impact tester (HV9250, Instron, maximum energy: 1603 J) and DWTT-impact tester (JL-50000, Weihai Manufacturing Co., Ltd), respectively. The Charpy impact tests were conducted in the temperature range of 20 °C to −120 °C at intervals of 20 °C, and DWTT tests were conducted at −15 °C. The fractographic morphology of fractured samples were observed by SEM. The crack path in samples were also observed by SEM after plating with a 20 μm thick layer of a nickel layer beneath the fracture surface.

3. Results

3.1. Microstructure

Fig. 3 shows micrographs of studied pipeline strips. It is generally accepted that AF nucleates intragranularly at dislocations or crystal defects in the deformed austenite, and is characterized by a needle-like structure in pipeline steels [19,20]. While, bainitic ferrite (BF) nucleates and transforms at the grain boundary of parent austenite, and has an irregular shape [21]. Based on this description, the TMCP-UFC processed strip predominantly comprised of AF, BF, and finely distributed M/A constituent at quarter and mid-thickness positions, as shown in Fig. 3 (a, b). In contrast, the TMCP-LC processed strip exhibited a completely different microstructural morphology at quarter and mid-thickness positions compared to TMCP-UFC. The microstructure mainly consisted of quasi-polygonal ferrite (QPF), degenerate pearlite (DP), and small fraction of BF, AF, and M/A constituent, as shown in Fig. 3

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

Elements	C	Si	Mn	P	S	Cr + Mo	Cu + Ni	Nb + V + Ti	Fe
%	0.061	0.11	1.75	0.0079	0.0014	0.49	0.30	0.094	balance