Effects of Cooling Paths on Through-Thickness Microstructure and Mechanical Properties of Heavy Gauge X80 Pipeline Steel

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Received: 23 October 2016/Revised: 6 December 2016/Published online: 1 March 2017
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Abstract The effects of various cooling paths on uniformity of through-thickness microstructure and mechanical properties of X80 pipeline steel of 22.0 mm in thickness were studied. The finite difference method was employed to calculate the temperature field during cooling. It was confirmed by the experimental result and temperature field calculation that the optimizing process was achieved by the ultra-fast cooling with medium cooling capacity (cooling rate of ~ 23 K/s) followed by ultimate cooling capacity (cooling rate of ~ 50 K/s). After optimization, the experimental steel displayed much uniform microstructure and the deviation of through-thickness hardness was controlled within 20 HV. In addition, the yield strength, tensile strength and elongation of the experimental steel were 621, 728 MPa and 21.5%, respectively, meeting the requirements of the API standard for X80 pipeline steels.

KEY WORDS: X80 pipeline steel; Ultra-fast cooling; Cooling path; Finite difference method; Microstructure; Mechanical properties

1 Introduction

Transportation of crude oil and gaseous fuel is required to be in a safe and cost-effective way from production areas to consumers [1]. Pipelines have been considered to be a very attractive option for crude oil and gas transportation [2]. In recent years, the heavy gauge X80 pipeline steel has become the main choice in long-distance pipeline projects around the world [3].

Thermo-mechanical controlled process (TMCP) technology is the main method used for pipeline steel production [4, 5]. In order to obtain a pipeline steel with good strength and toughness, a sufficiently high cooling rate is

necessary [6]. However, due to the poor cooling capacity of conventional laminar cooling (LC), the traditional heavy gauge X80 grade pipeline steels require a significant amount of alloy additions, e.g., Mo, Cr, Ni and Cu, for the increasing demand to satisfy the complicated environments [7]. Ultra-fast cooling (UFC) technology, characterized by high-strength cooling capacity, can effectively enhance insufficient cooling capacity of conventional laminar cooling, which has been applied in a variety of strip steel products, especially in high-grade and low-cost pipeline steels [8, 9]. Zhou et al. [10] investigated the X80 pipeline steel with reduced alloy consumption by UFC and found that similar microstructure and mechanical properties were obtained in the low-Mo steel by using UFC and in the high-Mo steel by LC. A research performed by Tian et al. [11] shows that UFC has much influence on the microstructure and mechanical properties of a X80 grade pipeline steel and the grain refinement strengthening is the main strengthening mechanism. However, the previous studies were mainly focused on the effects of the specific cooling path on the mechanical properties of the X80 steel by UFC,

Available online at <http://link.springer.com/journal/40195>.

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and the uniformity of through-thickness microstructure of the strip steel was not concerned. If UFC process is utilized in improper cooling paths, the heavy gauge X80 pipeline steel will produce an apparent temperature gradient leading to a distinct through-thickness hardness variation. Since the high surface hardness of X80 pipeline steels would increase the risk of surface cracking during service, surface hardness control of pipeline steels has attracted significant attention in industrial production. The appropriate selection of the cooling path, based on UFC, has been the critical for controlling the surface hardness and improving the through-thickness hardness uniformity of the strip steels.

In this work, on the basis of temperature field simulation, the homogeneity of through-thickness microstructure and mechanical properties cooled at various paths were firstly studied for X80 pipeline steels of 22 mm in thickness. The microstructure was then examined by scanning electron microscopy (SEM) and transmission electron microscopy (TEM), whereas the mechanical properties were investigated by tensile and impact tests. The microstructural features, strengthening and toughening mechanisms were finally discussed in detail.

2 Experimental Materials and Methodology

The square billets with dimensions of 130 mm × 130 mm × 200 mm were cut from an X80 grade continuous casting slab. The chemical composition of this steel is listed in Table 1.

Hot rolling experiments were conducted on a hot rolling platform consisting of a ϕ 450-mm hot rolling mill and cooling system. The cooling system has 4 units and each single unit is equipped with flow regulators which are able to control the cooling rate of the strip steel. The schematic presentation of both rolling and cooling conditions is presented in Fig. 1.

The steel slabs were placed in a box heating furnace, and they were heated at 1473 K for 2 h followed by hot rolling. The hot rolling has two stages, i.e., γ recrystallization zone and γ non-recrystallization zone. At the first stage (γ recrystallization zone), the starting rolling temperature is 1393 K and the total thickness reduction is 53.9%, whereas at the second stage the starting and finishing rolling temperatures are 1203 and 1103 K, respectively. The final thickness of strip steel is 22.0 mm. After hot rolling, the

Fig. 1 Schematic illustration of the rolling and cooling conditions

strip steels were promptly cooled by the cooling system on the run-out table. The cooling rate was controlled by water flux adjustment as three different processes simulation: (1) LC process; (2) UFC with ultimate cooling capacity followed by medium cooling capacity (Ult-Med UFC); and (3) UFC with medium cooling capacity followed by ultimate cooling capacity (Med-Ult UFC). The cooling rates of UFC with ultimate cooling capacity and medium cooling capacity were approximately 50 and 23 K/s, respectively. Finally, the strip steels were cooled to 793 K and consequently air-cooled to room temperature.

Metallographic specimens were cut off at the 1/4 of the width of the rolling direction. The specimens were grinded, polished and etched by a 4 vol% nital solution. Through-thickness microstructure of the strip steels was observed by a ZEISS ULTRA 55 field emission SEM. Specimens of ϕ 3 mm × 50 μ m were electro-polished in an electrolyte solution (9 vol% perchloric acid and alcohol) in a twin-jet apparatus and subsequently observed in a FEI Tecnai G2 F20 TEM. Tensile specimens were machined according to GB/T 228-2007 standard, which were prepared at 1/4 of strip width and 1/2 of strip thickness along rolling direction. Room-temperature tensile tests were conducted on a microcomputer controlled CMT5105-SANS electronic universal test machine. The V-notch Charpy impact specimens of 10 mm × 10 mm × 55 mm in size were prepared along the rolling direction at the 1/4 of thickness. The Charpy impact test was implemented at 253 K by a MTS ZBC2452-B pendulum impact tester. Through-thickness hardness was measured by a universal hardness tester with a 10-kg load.

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

C	Si	Mn	P	S	Nb	V	Ti	Cr	Mo	Fe
0.056	0.18	1.8	0.009	0.001	0.07	0.03	0.015	0.35	0.15	Bal.

Fig. 2 Schematic of region discretization

Based on the above difference equation, the through-thickness temperature field can be solved.

4 Results and Discussion

4.1 Simulation Results of Temperature Fields

The node spacing and time step were set as 2.4 mm and 0.05 s in the finite difference model, respectively. According to measured temperatures under various cooling processes, the convective heat transfer coefficient of each cooling unit could be calculated by the anti-inference method. Combined with the results of Moon [15], the calculated results of the convective heat transfer coefficients were 29 W/(m² K) at air cooling, 2000 W/(m² K) at LC, 7000 W/(m² K) at Med UFC and 16,000 W/(m² K) at Ult UFC, respectively.

The temperature field simulation results are presented in Fig. 3. As shown in Fig. 3a, during LC the surface temperature of strip steels was cooled down by cooling water impact. Since cooling efficiency of the remaining cooling water on the surface was significantly lower than cooling water impact, the surface temperature increased slightly during cooling headers clearance. The temperature difference between the surface and center of strip steels was

retained less than 176 K during the entire LC. However, due to cooling capacity limitation, 35 s was required for strip steel to cool down to 793 K and the cooling rate was relatively low with an average value of ~9 K/s. As shown in Fig. 3b, during Ult-Med UFC, the surface temperature of the strip steels was cooled down to 620 K in only 4.5 s after the initial cooling, with an average cooling rate of 108 K/s. In comparison, the cooling rate at 1/8 of thickness was 44 K/s, exhibiting an apparent difference. As shown in Fig. 3c, during Med-Ult UFC the difference in cooling rate between the surface and the 1/8 of thickness was apparently lower than that during Ult-Med UFC and the average cooling rate was 58 K/s when the surface temperature ranged between 1103 and 713 K. After Med UFC, the surface temperature of the steel strip decreased significantly and the temperature difference, between the strip surface and the 1/8 of thickness, increased.

4.2 Uniformity of Through-Thickness Microstructures

In Fig. 4, the through-thickness microstructures after LC are presented. Through-thickness microstructures were relatively uniform from the surface to the center of strip steels, consisting of quasi-polygonal ferrite, acicular ferrite and M-A islands. The lower through-thickness temperature gradient (Fig. 3a) contributed to relatively uniform microstructures. However, the low cooling rate during LC resulted in quasi-polygonal ferrites with relatively large sizes, possibly leading to lower strength [16].

The through-thickness microstructures of this pipeline steels obtained by Ult-Med UFC are presented in Fig. 5. The microstructures adjacent to the strip surface consisted of martensite and lath bainite indicating martensitic transformation around the surface. According to calculation results of JMatPro software, the initial phase transformation temperature (M_s) was 710 K. Based on the calculation results in Fig. 3b, the strip surface after cooling could sharply be cooled down to 647 K, a temperature significantly lower than the M_s , whereas the cooling rate was

Fig. 3 Temperature field simulation results: **a** LC, **b** Ult-Med UFC, **c** Med-Ult UFC

Fig. 4 Through-thickness microstructures obtained by LC: **a** surface, **b** thickness of 1/8, **c** thickness of 1/4, **d** thickness of 3/8, **e** thickness of 1/2

Fig. 5 Through-thickness microstructures obtained by Ult-Med UFC: **a** surface, **b** thickness of 1/8, **c** thickness of 1/4, **d** thickness of 3/8, **e** thickness of 1/2

higher than 100 K/s. Therefore, martensitic transformation was possible. However, the finishing cooling temperature at the 1/8 of thickness was always higher than 723 K and the martensitic transformation would be unable to occur. Consequently, the microstructure at the 1/8 of thickness (Fig. 5b) was mainly composed of bainite (acicular ferrite and M-A islands) and no martensite was observed. The microstructure at the 1/4–1/2 of thickness (Fig. 5c–e) was similar to that at the 1/8 of thickness, where bainite was

predominant. The fine and elongated bainitic ferrite grains were significantly beneficial to toughness than polygonal or quasi-polygonal ferrite grains [16]. Therefore, it could be concluded that the impact toughness of the experimental steel would be improved.

In Fig. 6, the through-thickness microstructures of pipeline steels achieved by Med-Ult UFC are presented where a uniform distribution of through-thickness microstructure could be observed. In Fig. 6a, the

Fig. 6 Through-thickness microstructures obtained by Med-Ult UFC: **a** surface, **b** thickness of 1/8, **c** thickness of 1/4, **d** thickness of 3/8, **e** thickness of 1/2

microstructure around the surface was mainly composed of bainite and no martensite was observed. The bainite was mainly lath bainite or acicular ferrite. Although surface temperature was decreased under the M_s (710 K) after hot rolling, the cooling rate was relatively lower than the cooling rate during Ult-Med UFC, leading to formation of acicular ferrite and quasi-polygonal ferrite. Therefore, martensitic transformation on the surface was effectively avoided in Med-Ult UFC. As shown in Fig. 6b–e, the microstructures of 1/8–1/2 in thickness were characterized by bainite (acicular ferrite and M-A islands). Compared to the steel obtained by Ult-Med UFC, the microstructures of 1/8–1/2 in thickness in this steel grade were significantly uniform, indicating better uniformity of through-thickness microstructure with the Med-Ult UFC.

To further analyze the variation of through-thickness microstructure, micromorphologies around the steel surfaces and in the center were observed in TEM. Figure 7a, b indicates that there are no significant changes in the microstructure between the strip surface and the center after LC. The microstructure was mainly composed of bainite ferrite with abundant dislocations. During Ult-Med UFC, a high amount of lath martensite phases existed on the surface (Fig. 7c) due to fast cooling rate. However, polygonal and acicular ferrite structure (Fig. 7d) was observed in the center, attributed to low cooling rates. As a result, the through-thickness microstructure was significantly different during Ult-Med UFC. During Med-Ult UFC, the TEM micrographs from surfaces and centers were similar (Fig. 7e, f), being mainly composed of bainite

ferrite with a high density of dislocations. Compared to microstructures obtained by LC, finer bainite ferrite phases were observed in an acicular shape, resulting in higher strength and toughness.

In order to obtain heavy gauge pipeline steels with uniform microstructures, a proper cooling rate after hot rolling should be adopted for phase transformations from austenite to acicular ferrite or bainite on the surface to be ensured, whereas a subsequently higher cooling rate for phase transformations of polygonal ferrites should be avoided and fine acicular ferrite or bainite produced in center.

4.3 Effects of Cooling Paths on Mechanical Properties of Pipeline Steels

The tensile properties of the experimental steels are presented in Table 3. During LC, steels displayed the lowest yield ($R_{t0.5}$), tensile strength (R_m) and the highest elongation. The value of the yield strength did not meet the requirement of API standard for X80 pipeline steels. On the contrary, the tensile properties of pipeline steels obtained from the other two processes are in accordance with the API standard of X80 pipeline steels. Compared to LC, the yield and tensile strength of steel during Ult-Med UFC increased from 542 to 610 MPa and from 677 to 719 MPa, respectively, whereas elongation decreased from 23 to 21%. The main reason was that the UFC process inhibited phase transformation of bulky polygons and quasi-polygonal ferrite and promoted phase transformations of fine acicular ferrite and bainite. In

Fig. 7 TEM micrographs of steels: **a** surface of LC process, **b** center of LC process, **c** surface of Ult-Med UFC process, **d** center of Ult-Med UFC process, **e** surface of Med-Ult UFC process, **f** center of Med-Ult UFC process

Table 3 Mechanical properties of the experimental steels cooled at various paths

Cooling process	$R_{t0.5}$ (MPa)	R_m (MPa)	A_{50} (%)	vE at 253 K (J)
LC	542	677	23	235, 220, 263
Ult-Med UFC	610	719	21	282, 289, 280
Med-Ult UFC	621	728	21.5	289, 294, 291
API X80	552–690	621–827	15	≥ 145 (268 K)

addition, it was observed that the strength and elongation of steels obtained during Med-Ult UFC were slightly better than that during Ult-Med UFC.

As listed in Table 3, all Charpy impact energies (vE) of steels met the API standard of X80 pipeline steels. The Charpy impact energy at 253 K obtained by LC was the lowest, with an average of 239 J, and that obtained by Ult-Med UFC and Med-Ult UFC was similar in value, with the averages of 284 and 291 J, respectively. Through TMCP technology, Deng *et al.* [17] obtained a 16-mm-thick X80 pipeline steel with a similar chemical composition, whose impact energy at 253 K was 235 J. On the contrary, the heavy gauge X80 pipeline obtained a good toughness under both Ult-Med UFC and the Med-Ult UFC. In addition,

during Med-Ult UFC, the experimental steel displayed the best impact toughness. This result was in agreement with results obtained by Sanchez [16] that the finer the grain size and the more uniform through-thickness microstructure, the better the toughness of pipeline steels. In Figs. 8, 9 and 10, the SEM micrographs of the impact fracture at 253 K are presented. The fracture morphology of steel surfaces was dominated by dimples. The highly magnified fractographs at the fracture surface centers (region A) and shear lip zones (region B) are also presented in Figs. 8, 9 and 10. From Figs. 8b, 9b and 10b, it was observed that the size of dimples at region A obtained by Ult-Med and Med-Ult UFC was larger than that obtained by LC. In region B, the proportion of large dimples for steels obtained by Ult-

Fig. 8 Impact specimen fractographs obtained by LC: **a** low-magnification fractographs, **b** high-magnification fractographs of region A, **c** high-magnification fractographs of region B, **d** low-magnification fractographs of delamination, **e** high-magnification fractographs of delamination surface (region C)

Fig. 9 Impact specimen fractographs obtained by Ult-Med UFC: **a** low-magnification fractographs, **b** high-magnification fractographs of region A, **c** high-magnification fractographs of region B

Med and Med-Ult UFC was higher than the proportions obtained by LC. These large dimples might be attributed to the small grain sizes and were conducive to impact toughness [18, 19]. The fracture surface of the steels produced by LC exhibited severe delamination (Fig. 8d). Some researchers also reported this delamination behavior in Charpy specimens [20–22]. The highly magnified fractographs (Fig. 8f) showed that the surfaces of delamination consisted of cleavage facets, suggesting brittle fracture. Some literatures indicated that delamination at lower temperatures could increase the impact toughness of steels

[23, 24]. However, in this study, the delamination of steels during LC occurred at a relatively higher impact temperature (253 K), where the fracture is still dominated by ductile behavior. It was reported that the severe delamination in the ductile region led to impact energy reduction [25, 26]. The reason might be due to the existence of a low amount of plastic deformation in the delamination area [27]. In steels obtained by Ult-Med and Med-Ult UFC, the delamination was inconspicuous or could not even be observed. Therefore, steels obtained by Ult-Med and Med-Ult UFC presented the higher νE .

Fig. 10 Impact specimen fractographs obtained by Med-Ult UFC: **a** low-magnification fractographs, **b** high-magnification fractographs of region A, **c** high-magnification fractographs of region B

Fig. 11 Through-thickness HV distributions during various cooling paths

The through-thickness hardness distributions are presented in Fig. 11. The hardness distributions during these three processes exhibited a similar trend of higher surface and lower center hardness. The microstructure alterations were resulted mainly from through-thickness structure discrepancy due to differences in cooling rate and temperature gradient. However, hardness differences between the surface and center regions during different processes were apparently different. The HVs (Vickers hardness) of heavy gauge pipeline steels cooled down during LC technology, distributed more uniformly with an average of 205–220 HV, due to relatively uniformed through-thickness microstructures. However, during Ult-Med UFC cooling, hardness distributions were severely non-uniform. The average HV value was higher than 300 HV at the surface, but significantly decreased at the 1/8 of thickness, mainly due to remarkable microstructure differences between the surface and the 1/8 of thickness. The microstructure on the surface layer was mainly composed of high hardness martensite. At the 1/8 of thickness, the

HV values significantly reduced due to insufficient martensite. Within the thickness of 1/8 and 1/2, the microstructure was more uniform and the hardness was in the range of 221–242 HV. Regarding heavy gauge pipeline steels cooled at Med-Ult UFC, through-thickness hardness distributions were uniform and the average hardness value was in the range of 225–243 HV. Therefore, by Med-Ult UFC adaptation, heavy gauge pipeline steels with uniform through-thickness properties could be obtained. Med-Ult UFC was the optimum post-rolling cooling process for heavy gauge X80 pipeline steels.

5 Conclusions

1. By using the LC process, the microstructure through thickness of the strip was relatively uniform and consisted of quasi-polygonal ferrite, acicular ferrite and M-A island. However, the mechanical properties were poor. For example, the yield strength, tensile strength and impact energy (257 K) were decreased by 80, 40 MPa and 45 J than the samples cooled down by ultra-fast cooling, respectively.
2. Utilizing the Ult-Med UFC process, the yield strength, tensile strength and impact energy (257 K) of the steel were 610, 719 MPa and 284 J, respectively, satisfying the API standard of X80 pipeline steels. However, the high hardness martensite layer was formed due to the high cooling rate after hot rolling, which resulted in the significant deviations in through-thickness microstructure and mechanical properties.
3. With Med-Ult UFC process, the bainite phase transformation on strip surface was basically completed during a moderate cooling rate, avoiding the high hardness of strip surface. The subsequently high cooling rate led to the bainite in 1/2 of thickness of the strip. Therefore, the microstructure through thickness was uniform and the mechanical properties of the

steel were excellent. The deviation of through-thickness hardness was controlled within 20 HV, and both the strength and impact energy were slightly higher than the steels produced by Ult-Med UFC.

Acknowledgements This work was financially supported by the National Natural Science Foundation of China (No. 51234002) and the Fundamental Research Funds for the Central Universities (N130407001).

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