RESEARCH AND DEVELOPMENT OF ULTRA-HIGH STRENGTH X100 WELDED PIPE

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Abstract

Ultra-high strength X100 welded pipe can be used in the construction of long distance oil and gas pipeline to improve transmission capacity and reduce operation cost. By using the way of thermo-simulation and pilot rolling, the CCT (Continuous Cooling Transformation) diagram and the relationship between ACC (Accelerated Cooling) parameters, microstructure and mechanical properties were studied for the designed X100 pipeline steel with low carbon, high manganese and niobium micro-alloyed composition in lab. The analysis of CCT diagram indicates that the suitable hardness and microstructure can be obtained in the cooling rate of 20~80℃/sec. The pilot rolling results show that the ACC cooling start temperature below Ar3 phase transformation point is beneficial to increase uniform elongation, and the cooling stop temperature of 150~350℃ is helpful to obtain high strength and toughness combination. Based on the research conclusions, the X100 plate and UOE pipe with dimension in O.D.1219×W.T.14.8mm, O.D.1219×W.T.17.8mm, designed for the natural gas transmission pipeline, were trial produced. The manufactured pipe body impact absorbed energy at -10℃ is over 250J. The DWTT shear area ratio at 0℃ is over 85%. The transverse strength meets the X100 grade requirement, and uniform elongation is over 4%.The X100 plate and UOE pipe with dimension in O.D.711×W.T.20.0mm, O.D.711×W.T.12.5mm, designed for an offshore engineering, were also trial produced. The average impact absorbed energy of pipe body at -30℃ is over 200J. The average impact absorbed energy of HAZ (Heat-affected zone) and WM (Welded Seam) at -30℃ is over 100J. And the good pipe shapes were obtained

Introduction

It is benefical to reduce the cost for long distance oil and gas transmission pipeline by using high strength, large diameter line pipe [1]. Higher strength pipeline steel would be required for the construction of larger transmission capacity pipeline in the future. There are about 30 year's histories for the investigation on development and application of the high strength pipeline steel. Nowadays, X80 grade line pipe has been applied in a large scale successfully. Many studies have also been done for the higher grade X90, X100 and X120 pipeline steel in the last several decades, however, those steels haven't been put into application widely due to the complication of evaluating the operation reliability [2-5]. In 2007, it is the first time to define the X90, X100 and X120 grade in the API 5L specifications [6], which provide the reference to use ultra-high strength pipeline steel in engineering. Some studies show that the combination of high deformability and toughness of ultra-high welded pipe is required for the operation safety [7]. As a result, it is a challenge to develop the materials, rolling, forming and welding process of the welded pipe.

By using the way of thermo-mechanical simulation and pilot rolling, the deformed austenite dynamic continuous cooling transformation and the relationship between ACC processes, mechanical properties and microstructure of X100 grade pipeline steel were studied in this paper. The manufacturing process and mechanical properties of trial produced X100 UOE welded pipe were introduced.

Experimental research of X100 pipeline steel

Alloy design and chemical composition

Low carbon, high manganese and niobium micro-alloyed composition is the standard alloy design for high strength pipeline steel in order to fulfill the better matching of strength and toughness. In this case, niobium is the distinguished alloy due to its roles of retardation of recrystallisation and precipitation [8]. The improved strength and toughness of the steel result from the metallurgical mechanism of grain refinement, solid solution, dislocation and particle precipitation combined with TMCP process. This concept has been used in the development and production of high strength up to X80 grade pipeline steel in large scale [8~10].

Based on the concept above, ultra-high strength X100 pipeline steel was designed. The experimental steel was melted by 500kg vacuum melting furnace in lab. Table 1 show the chemical composition. The carbon content of 0.051% is close to the regular level of X80 composition considering the improvement of centerlline segregation, toughness and weldability. Higher manganese content of 1.96% is necessary to compensate the lack of the strength due to the low carbon contained. The 0.054% niobium content is the results of balancing the solid solution, precipitation and economy. Other alloys, such as Ni, Cr, Mo, are additional to control the phase transformation and strength compensation. What's more, the technologies of Ca treatment, micro Ti treatment and clean steel making with low P, low S content were applied in this steel. The carbon equivalent CEpcm is about 0.20%, which enable the steel to get good longitudinal and girth weldability.

Table 1. Composition of X100 pipeline steel in lab (w.t. %)

C	Si	Mn	P	S	NB	Others	CEpcm
0.051	0.22	1.96	≤0.010	≤0.001	0.054	Ni、Cr、Mo、Ti	0.20

Dynamic continuous cooling transformation

The approach of thermo-mechanical simulation was used to analysis the dynamical continuous cooling transformation of X100 pipeline steel by using Gleeble-3800 machine. The effect of cooling rate after two-stage deformation on microstructure and Hv10 hardness were studied. The CCT curve and the relationship between the cooling rate, hardness HV10 and corresponded microstructure were shown in Figure 1 and Figure 2 respectively. When the cooling rate is less than 0.5℃/sec, the polygonal ferrite and bainite microstructure were observed. When the cooling rate is above 0.5℃/sec, the single bainite microstructure formed in steel. Especially, there are an obvious decline in phase transformation temperature and an increase in hardness when the cooling rate is greater than 5℃/sec. The suitable hardness of 300~350Hv10 and the refined microstructure for X100 steel could be developed within the cooling rate of 20~80℃/sec.

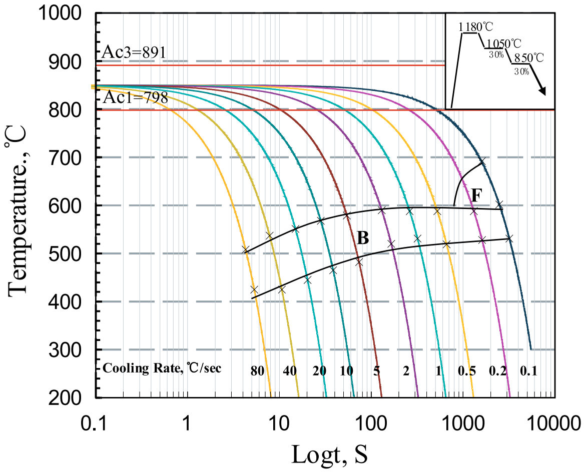


Figure 1. Dynamic CCT curves

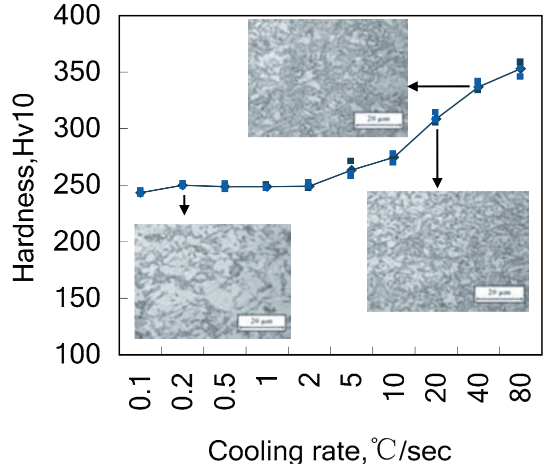


Figure 2. Effect of cooling rate on hardness and microstructure

Experimental processes and mechanical properties

The experimental rolling was conducted using pilot single reversing mill with 550 mm outside diameter roller. The TMCP processes were applied. And the relationship between ACC start cooling temperature, stop cooling temperature, microstructure and mechanical properties of X100 pipeline steel were investigated. Reheating temperature is 1180 ℃ . Final rolling temperature is about 790℃. The thickness of steel plate is 16mm. Figure 3 indicates the effect of start cooling temperature on the tensile and impact toughness. There are much more effects on the yield strength, uniform elongation and toughness rather than tensile strength. With the start cooling temperature decreasing to below Ar3 point, the yield strength and impact energy drop obviously, while the uniform elongation increases, all of which can be explained in the light of the phase transformation. When the start cooling temperature is over Ar3, the microstructure is almost 100% bainitic (Figure 4a), which contribute to provide the high strength and toughness for the steel, however, the uniform elongation tends to decline because of the intensive work hardening induced by the interaction between the free C, N atoms and high density dislocation in bainite. If the start cooling temperature is below Ar3, the ferrite-bainite dual-phase microstructure forms (Figure 4b) in the case, which has a positive influence on improving the uniform elongation from the view of the micromechanics theory [11]. However, the yield strength decreases because the ferrite phase is easy to deform, and the toughness decline due to the difference of the hardness between the ferrite and bainite microstructure. Figure 5 shows the effect of stop cooling temperature on the mechanical properties. With the stop cooling temperature decreasing, the tensile strength increases evidently, while the yield strength and impact energy tend to degrade. Especially, the anisotropy of strength between transverse and longitudinal specimens became more notable in the lower temperature. The tensile strength meets the requirements for X100 pipe manufacturing when the stop cooling temperature is ranging from 150 ℃ to 350 ℃ . Figure 6 presents the microstructure obtained in various stop cooling temperature. The evolution of microstructure is observed from coarse acicular ferrite to fine bainite with the stop cooling temperature decreasing.

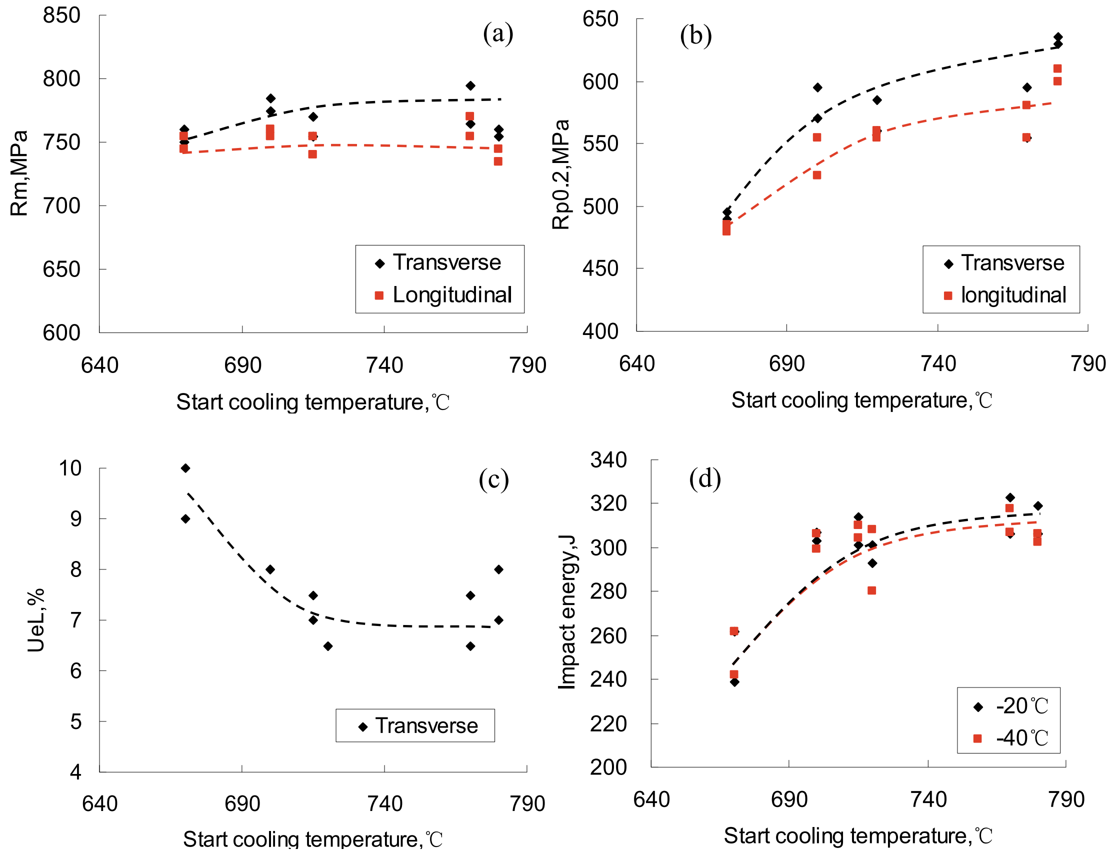


Figure 3. Effect of start cooling temperature on mechanical properties (a) Rm (b)$R_{p0.2}$ (c) Uniform elongation (d) CVN absorb energy

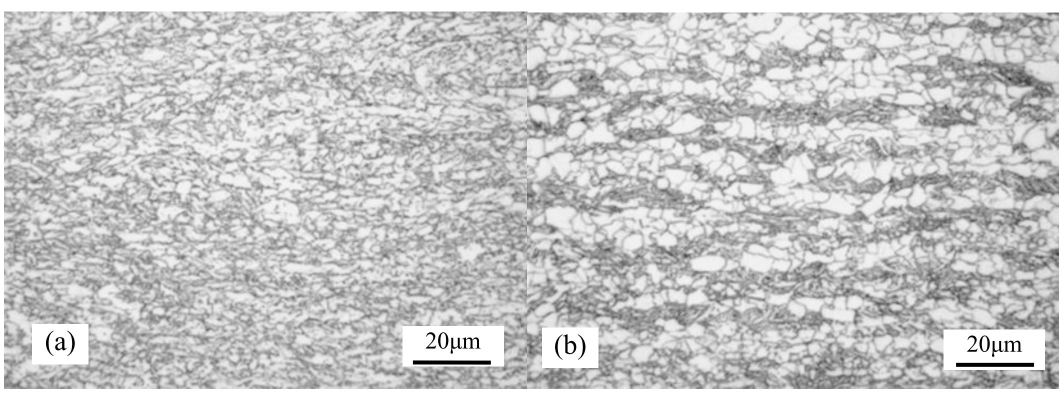
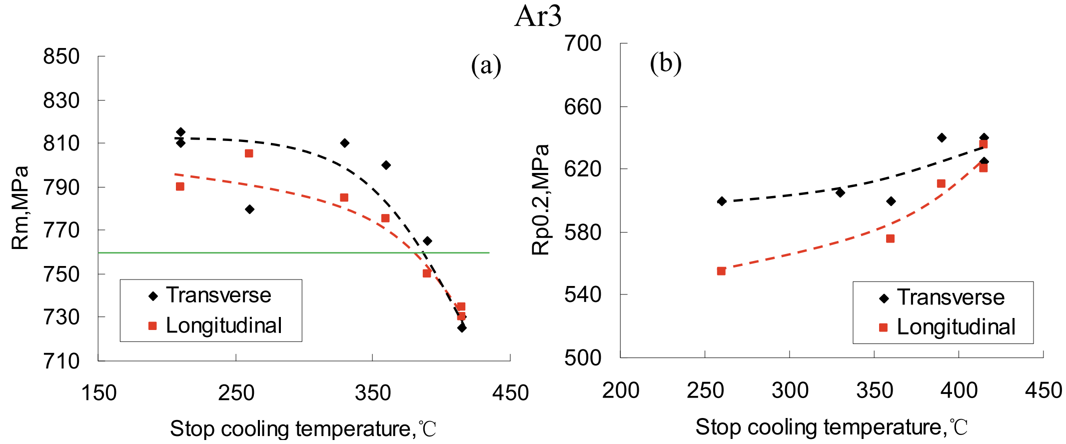


Figure 4. Microstructure observed in different start cooling temperature (a) Above Ar3 (b)Below Ar3



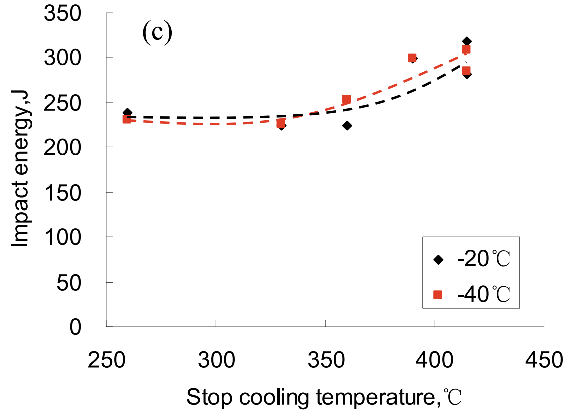


Figure 5. Effect of stop cooling temperature on mechanical properties (a)R_m (b) $R_{p0.2}$ (c) CVN absorbed energy

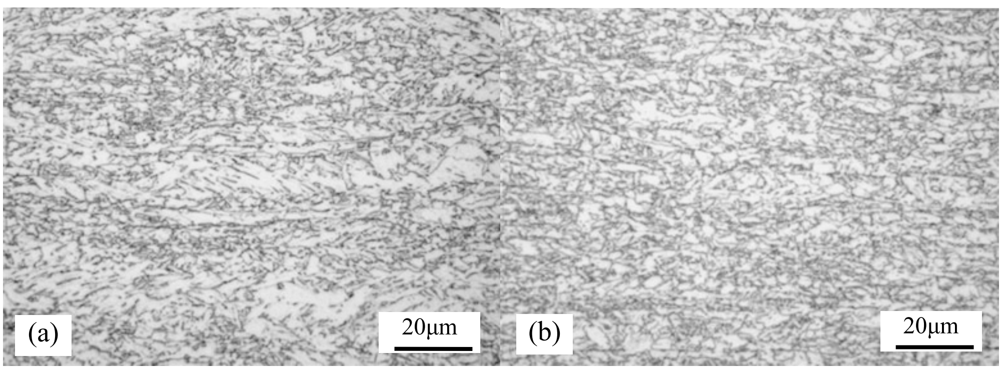


Figure 6. Microstructure observed in different stop cooling temperature (a) 415℃ (b) 260℃

Trial production of X100 UOE welded pipe

Manufacturing processes of UOE pipe

The integrated manufacturing process for UOE pipe is shown in Figure 7. Baosteel has the advanced production facilities ranging from steel making, continuous casting, plate rolling to pipe making. 300tons converters and LF+RH (Ladle Furnance plus Ruhrstahl-Heraeus) refining processes are used for the clean steel making. There are various continuous slabs with thickness of 220~300mm prepared for the production of pipeline steel plate. 5m heavy plate mill with maximum 10000 tons rolling force and the technology of ultrasonic nondestructive detection covering whole plate give a guarantee to provide high quality skelp materials. The main equipment of UOE mill was introduced from Germany and Sweden. The maximum capacities of C, U, O forming machine are 4000, 3250, 72000 tons, respectively. All pipes should be nondestructive detected by using ultrasonic wave, x-ray and magnetic particle before delivery. Four levels computer management system ensures the high efficiency of pipe making and information traceability.

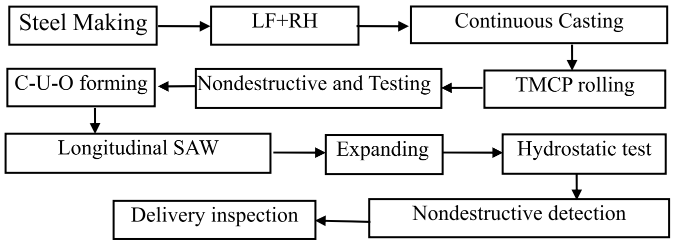


Figure 7. Integrated manufacturing processes

<u>Trial production of X100 UOE pipe with O.D.1219mm</u>

Based on the demand of future pipeline with larger transmissions capacity, the X100 steel plate and UOE pipe with O.D.1219×W.T.14.8mm, O.D.1219×W.T.17.8mm were trial produced at Baosteel. The steel plate was produced in 5m heavy plate mill and the critical parameters were determinated according to the previous experimental results. The start cooling temperature of slightly below Ar3 was chosen after thermo-mechanical rolling, which aims to improve the plasticity of the steel. The dual phase microstructure generates in trial produced plate. The uniform elongation of each plate is more than 7% in transverse tensile test as shown in table 2, and the tensile strength of over 800MPa is enough for X100 grade pipe making. Meanwhile, the full size Charpy-v-notch(CVN) impact absorbed energy is over 250J@ -20℃, and the Drop weight tear test (DWTT) property is over 85%@-15℃, all of which are satisfied with the producing requirements of X100 pipe.

Table 2. Mechanical properties of steel plate (Transverse)

Thickness, mm	Tensile				CVN@-20℃	DWTT@-15℃
	R_m,MPa	$R_{p0.2}$,MPa	Y/T	Uel%	Energy,J	SA,%
14.8	816	692	0.85	8	268~272	96
17.8	803	658	0.82	7	303~345	87

The X100 welded pipes were trial manufactured in UOE mill. The excellent strength, toughness in the pipe body and weld seam were realized as given in table 3. Comparing the mechanical properties between the pipe and plate, there are a yield strength and tensile strength shift of about +60~100Mpa and 0~-14MPa, respectively. The change in both yield and tensile strength during pipe production resulted in a negligible shift in Y/T ration and uniform elongation. The Y/T increases to 0.94~0.95, and the uniform elongation drops to 4.4~4.7%, however, all of which meet the specifications. What's more, transverse CVN and DWTT impact toughness in both pipe body and weld seam were excellent to satisfy the toughness requirements.

Table 3. Mechanical properties of UOE pipe (Transverse)

Dimensions O.D.*W.T., mm	Tensile					CVN energy @-10℃			DWTT@0℃
	Pipe body				WM	Pipe body	WM	HAZ	SA,%
	R_m,MPa	$R_{p0.2}$,MPa	Y/T	Uel,%	R_m,MPa	,J	,J	,J	
1219*14.8	802	760	0.95	4.4	818	263~355	102~152	102~176	98
1219*17.8	803	756	0.94	4.7	792	252~278	150~164	153~189	93
Requirments	760~990	690~840	≤0.96	≥4	≥760	≥220	≥80	≥80	≥85

<u>Trial production of X100 UOE pipe with O.D.711mm</u>

Based on the successful trial production of large diameter X100 UOE pipe, smaller dimensions X100 pipe with O.D.711 × W.T.12.5mm, O.D.711 × W.T.20.0mm were trial produced and accomplished commercial production according to the demand of an offshore engineering. Considering the requirements of higher CVN impact toughness at -40℃ for the plate, the start cooling temperatures of over Ar3 point and lower stop cooling temperature were used. The designed microstructure characterized by refined single bainite was observed. Table 4 lists the typical mechanical properties of the steel plate. In comparison with the results of trial produced plate above, the ultimate tensile strength is close, while the yield strength is slightly higher resulting from the microstructure difference. Meanwhile, the CVN toughness still keeps high values of 270~302J although the testing temperature is down to -40℃ and the full thickness DWTT properties are over 85%@-15℃.

Table 4. Mechanical properties of steel plate (Transverse)

Thickness, mm	Tensile			CVN@-40℃	DWTT@-15℃
	R_m,MPa	$R_{p0,2}$,MPa	Y/T	Energy, J	SA,%
12.5	813	697	0.86	270~290	99
20.0	825	686	0.83	291~302	86

Several hundred tons X100 pipe were also produced in UOE mill. The average mechanical properties of the mass production pipe are shown in table 5. The average strength in both pipe body and weld seam were approximate to the results of trial produced pipe above. The average CVN impact absorbed energy at -30℃ of pipe body, weld seam and heat affect zone (HAZ) are over 210J, 100J and 130J, respectively. The DWTT properties are over 85%@-15℃. All of the tensile strength and impact toughness are well satisfied with the requirements of API 5L specification. What's more, the geometric dimensions of some pipe were measured manually, and the typical results were introduced in table 6. There are a little difference between the N-end and S-end in the outside diameters, out of roundness, wall thickness and misalignment. The welded bead and the full length straightness of the pipe are far lower than the upper limitation. It can be concluded that either the weld seam geometry or the pipe dimensions was excellent fulfilled with the API 5L specification.

Table 5. Mechanical properties of UOE pipe (Transverse)

Dimensions O.D.*W.T., mm	Tensile				Average CVN energy@-30℃			DWTT@-5℃
	Pipe body			WM	Pipe body	WM	HAZ	SA,%
	R_m,MPa	$R_{p0,2}$,MPa	Y/T	R_m,MPa	J	J	J	
711*20.0	800	734	0.92	833	211~234	101~109	157~179	95
711*12.5	821	782	0.95	804	227~248	150~162	131~143	86
API 5L	760~990	690~840	≤0.97	≥760	≥40	≥40	≥40	≥85

Table 6. Geometric deviation and dimensions

Nominal dimensions O.D.*W.T., mm	Pipe except the end				N-end				S-end			
	Out side diameter, mm	Internal bead, mm	External bead, mm	Full-length straightness, mm	Out side diameter, mm	Wall thickness, mm	Out of roundness	Misalignment, mm	Out side diameter, mm	Wall thickness, mm	Out of roundness	Misalignment, mm
711*20.0	711.0	2.4	2.5	2.0	711.3	20.1	0.36D%	0.44	711.4	20.1	0.39D%	0.51
711*12.5	711.2	2.2	2.3	3.9	711.5	12.8	0.41D%	0.25	711.5	12.8	0.40D%	0.26
API Specification	±3.6	≤3.5	≤3.5	≤24	±1.6	±0.1t	1.0D%	≤3	±1.6	±0.1t	1.0D%	≤3

Conclusions

The approach of thermo-mechanic simulation and pilot rolling were used to research the dynamic continuous cooling transformation of deformed austenite and the relationship between ACC processes and mechanical properties of X100 pipeline steel. The influence of key processing parameters on the microstructure and mechanical properties of X100 steel plate was investigated.

The microstructures and mechanical properties are strongly influenced by the start cooling temperature, stop cooling temperature and cooling rate after thermo-mechanical rolling. The single bainite phase microstructure could be obtained by controlling the ACC start cooling temperature over Ar3 point, which is beneficial to get the combination of high strength and toughness for X100 steel. The ferrite-bainite dual phase microstructure could be observed when the start cooling temperature is lower than Ar3 point, which is helpful to improve the uniform elongation of the steel. The cooling rate of 20~80℃/sec and the stop cooling temperature of 150~350℃ are required for X100 steel to get the suitable microstructure and properties.

The integrated manufacturing process for UOE pipe in Baosteel was briefly introduced. The X100 UOE welded pipes with O.D.1219×W.T.14.8mm, O.D.1219×W.T.17.8mm were trial produced, and the mechanical properties are characterized by high strength, high impact energy and good plasticity. Meanwhile, the smaller size X100 UOE pipe with O.D.711×W.T.20.0mm, O.D.711×W.T.12.5mm were commercial produced in small scale. High CVN toughness at -30℃ and good pipe geometric dimensions were obtained.

Reference

[1] H-G. Hillenbrand and C. Kalwa ,"Production and Service behavior of High Strength Large Diameter Pipes," Proceedings of International Conference on the Application and Evaluation of High-Grade Line pipes in Hostile Environments, ed. M. Toyoda and R. Denys(Yokohama, Japan: Scientific Surveys Ltd., 2002), 203-215.

[2] Hitoshi Asahi, "Overview of Development and Commercialization of X120 Ultra-High Strength UOE Linepipe," Proceedins of International Symposium on Micro-alloyed Steels for Oil & Gas Industry, (Araxa-MG, Brazil:Edited by TMS,2006),24-26.

[3] J. Zhou, D.M. Duan, D. Taylor, "Some considerations for successful applications of high grade line pipes" (Paper presented at the International Seminar on Application of high strength Line pipe, Xi'an,China, 2010), 28-29.

[4] G. Demofonti et al, "Evaluation of the suitability of X100 pipes for high pressure gas transmission pipelines by full scale tests" Proceedings of International Pipeline Conference 2004, (Calgary Alberta, Canada:IPC, 2004), 0415.

[5] L. Andreas, K. Gerhard, "Investigation of the Stress-strain Behaviour of Large-Diameter X100 Linepipe in view of Stain-based Design Requirments" Proceedins of International Pipeline Conference 2008, (Calgary Alberta, Canada: IPC,2008), 64553.

[6] Specification for Line pipe. ANSI/API Specification 5L, Forty Fourth Edition, (Washington: API Publishing Services, 2007).

[7] H. L. LI et al., “Strain based Design for Pipeline and Development of Pipe Steels with High Deformation Resistance,” Welded Pipe and Tube, 30(5) (2007),5-11.

[8] D. G. Stalheim and J. M. Gray, “Ferrite/ Acicular Ferrite Alloy Designs for API X80 Gas Transmission Linepipe Steels”(Paper presented at the International Seminar: Modern Steels for Gas and Oil Transmission Pipelines, Moscow, Russia, 2006).

[9] C.G. Zhang et al., “Recent Development of Large Diameter X80 UOE Line Pipe,” Baosteel Technical Research, 4(3) (2014), 20-26.

[10] L. Zheng et al., ”Development of High Nb X80 grade Pipeline Steel wide-thick plate used in the Second West to Eeast Gas Pipeline Project,” Welded pipe and tube, 32(4)(2009),25-29.

[11] J. Huper et al.,“Effect of Volume Fraction of Constituent Phases on the Stress-strain Relationship of Dual Phase Steels,” ISIJ International, 39 (3) (1999), 288-294.