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A Study on the Characterization of Mechanical Properties of Grade X80 High Strain Line Pipe Steel

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Abstract

This paper introduces mechanical and metallurgical properties of 27mm thick Grade X80 high strain line pipe steel which aims at constructing long distance natural gas over permafrost and seismic areas. The steel is molybdenum and boron free. Dual phase of the X80 steel plates are regulated by thermal-mechanical controlled processing. The outer diameter of 1219mm pipes are manufactured by UOE process. DWTT toughness and longitudinal tensile properties including the Rt0.5/Rm, Rt1.5/Rt0.5 and Rt2.0/Rt1.0 are analyzed on both the plates and the pipes. Strain aging properties are also evaluated on the base material of the pipe, demonstrating that the pipe complies well with the pipeline construction requirements. Strengthening effects of precipitates are analyzed, revealing a 58.1MPa strengthening contribution by precipitates less than 20nm in size. Dislocation hardening is approximately 176MPa in the present studied steel.

Keywords: High Strain; Line Pipe; Dual Phase Microstructure; Uniform Elongation; Precipitation; Dislocation Hardening

1 INTRODUCTION

The world's most attractive natural gas fields are far away from its ultimate consumers. Long distance gas transportation by pipeline often goes through harsh climate and complicated geological regions, such as the earthquake zone, permafrost areas and other areas prone to mudslides and impending collapse due to unsteady geological conditions. In such unstable regions, the pipeline is exposed to complicated stress conditions and should have sufficient resistance against buckling and/or weld fracture if there is large ground movement. Its deformation ability directly affects the safety and reliability of gas transportation. Therefore, the original pipeline design scheme based on stress is not suitable [1]. As a result, people put forward the strain-based design concept on account of pipeline integrity assessments. In this case, it is important to ensure that the maximum allowable global strain is greater than the strain imposed on the pipeline. Meanwhile, high strength steels (X70 and beyond) with sufficient toughness and ductility are needed to improve transportation capacity. To this end, it is essential that the line pipe steel for manufacturing pipeline should have high strength, high longitudinal uniform elongation, low yield to tensile (Y/T) ratio etc [2-4].

High strength steels for line pipe manufacturing purposes have normally low-carbon content (less than 0.1wt% C), and are processed by niobium, vanadium and titanium micro-alloying during steel making. Thermal-mechanical controlled processing (TMCP) is the conventional processing technology for high strength line pipe steels. In order to achieve effective microstructure refinement during controlled rolling and cooling of steel, copper, nickel and molybdenum are often added in steel making to suppress austenite recrystallization and to obtain precipitation hardening during the hot steel processing[1, 5]. In the case of line pipe steel grades for strain-based applications, Bainite-Ferrite dual-phase microstructure controlled by TMCP is a typical microstructure constituent to obtain the target strength, toughness and ductility [1-4, 6-8]. However, there is also considerable interest to reduce construction cost for long distance pipeline as well as safety and reliability of gas transportation between the line pipe steel suppliers and the pipeline engineering.

In this paper, 27mm thick Grade X80 high strain steel plate was developed by TMCP and characterized with dual phase microstructure. The steel is composed of 0.06C, 1.75Mn, 0.25Si, 0.30Cr, 0.20Ni, 0.25Cu, 0.015Ti and 0.065Nb (wt%). The pipe with outer diameter of 1219mm was manufactured by UOE process. Strain aging properties were verified on the pipe. Precipitation and hardening performance of the micro-alloying elements were also analyzed on the steel plate.

2 MECHANICAL PROPERTIES OF THE GRADE X80 HIGH STRAIN LINE PIPE STEEL

2.1 Microstructure of the Grade X80 Plate Steel for High Strain Line Pipe

Steel plates were manufactured in a double 4-high plate mill which is equipped with Multipurpose Interrupted Cooling Process (MULPIC). In order to obtain dual-phase microstructure, delaying period between finishing rolling and starting cooling was controlled from 70 to 110s according to the environment temperature so that the plate temperature was below ferrite transformation starting temperature. Figs. 1 (a) and (b) shows the microstructure of the 27mm Grade X80 Steel Plate for high strain line pipe. The microstructure of the steel plate is comprised of polygonal ferrite and granular bainite that are approximately 61% and 39% at 1/4 thickness, and 59% and 41% at 1/2 thickness respectively. Figs. 1 (c) and (d) illustrate microstructures of the steel plate by Transmission Electron Microscope (TEM). Precipitates are distributed uniformly in the inner grain and at the grain boundaries. In the meantime, high density dislocations and precipitates in the dislocations characterized precipitation behaviour.

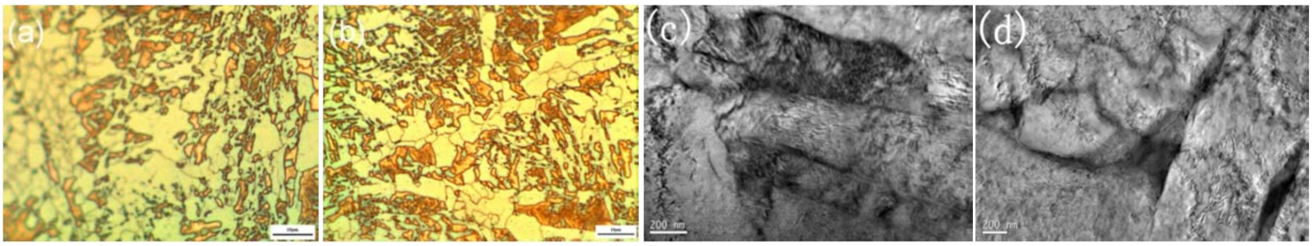

FIG.1 TYPICAL MICROSTRUCTURE OF THE X80 STEEL PLATE FOR HIGH STRAIN PIPELINE MANUFACTURING
(A) AND (C) AT 1/4 THICKNESS; (B) AND (D) AT 1/2 THICKNESS

2.2 Mechanical Properties of Base Material.

Transversal and longitudinal tensility tests were carried out on the pipe base materials. The transversal tensility tests were measured on the strip specimens. The longitudinal tests were on round bar specimens from which the testing coupons were heated at 205 to 235 degrees Celsius and kept for 5 minutes. Table 1 displays the mechanical properties of base materials of the X80 high strain line pipe. The results prove that both transversal and longitudinal tensile properties comply with the pipeline engineering requirements.

TABLE 1. MECHANICAL PROPERTIES OF THE X80 HIGH STRAIN LINE PIPE STEEL

	Transversal				Longitudinal						
	$R_{t0.5}$/MPa	R_m/MPa	A50/%	$R_{t0.5}$/ R_m	$R_{t0.5}$/MPa	R_m/MPa	A50/%	$R_{t0.5}$/ R_m	$R_{t1.5}/R_{t0.5}$	$R_{t2.0}/R_{t1.0}$	UEL/%
Min.	598	704	20	0.84	554	670	44	0.77	1.076	1.053	6.6
Max.	700	806	26	0.88	640	770	52	0.85	1.158	1.077	8.4
Ave.	646	751	24	0.86	552	729	48	0.82	1.107	1.063	7.4
Required	555-705	625-825	API	0.93	530-630	625-770	API	0.86	1.070	1.033	6.0

2.3 Toughness of the X80 High Strain Pipeline

Fig. 2 shows Charpy V-notch Impact absorbed energy at -10 degrees Celsius (CNV-10) of both the pipe base materials and welding materials with heat affected zones. In the base material of the pipe, the CNV-10 is from 200 to 350J with an average value of 282J. In the heat affected zone, CNV-10 value is between 74 to 329J with an average of 236J, complying with the requirement of single value larger than 60J and average value not less than 80J. DWTT results at -10 degrees Celsius reveal that the shearing area (SA%) value is from 85% to 95% with an average of 92%, exceeding the required value of 75%.

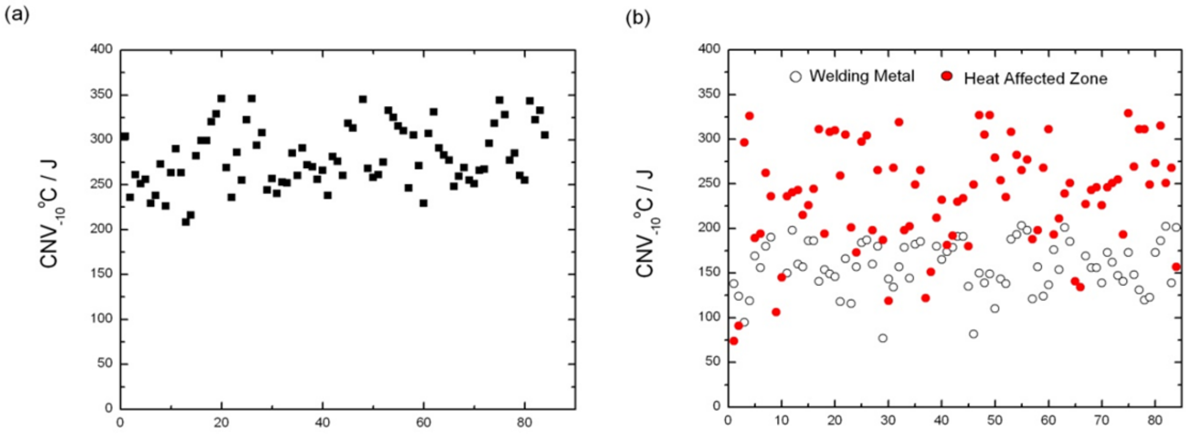

FIG. 2 CHARPY V-NOTCH IMPACT ABSORBED ENERGY OF THE PIPELINE. (A) BASE MATERIAL, (B) WELDING MATERIALS AND HEAT AFFECTED ZONE

2.4 Aging Behaviour of the Developed X80 High Strain Line Pipe Steel

Strain aging will occur during thermal coating on the cold deformed pipe. Many studies have been carried out on the aging effects of the high strain line pipe steels [7, 9-13]. It is reported that 'increment in the yield strength of pipes with a dual phase microstructure is larger than that with a single phase of granular bainite and the yield strength may increase up to 150MPa for X80 line pipe' [11]. In the present study, the authors use $R_{t1.5}/R_{t0.5}$ and $R_{t0.5}$ instead of Y/T and yield strength. $R_{t1.5}$ and $R_{t0.5}$ are respectively the stress at strains of 1.5% and 0.5%. Aging behavior is shown in Fig.3 by displaying the relationship among the uniform elongation (UEL), $R_{t1.5}/R_{t0.5}$ and the $R_{t0.5}$. After aging, longitudinal $R_{t0.5}$ increases at an average of 42MPa while the UEL reduces 1.1% on average. The stress ratio $R_{t1.5}/R_{t0.5}$ appears to have a reduction of 0.06, shown in Fig. 3(b).

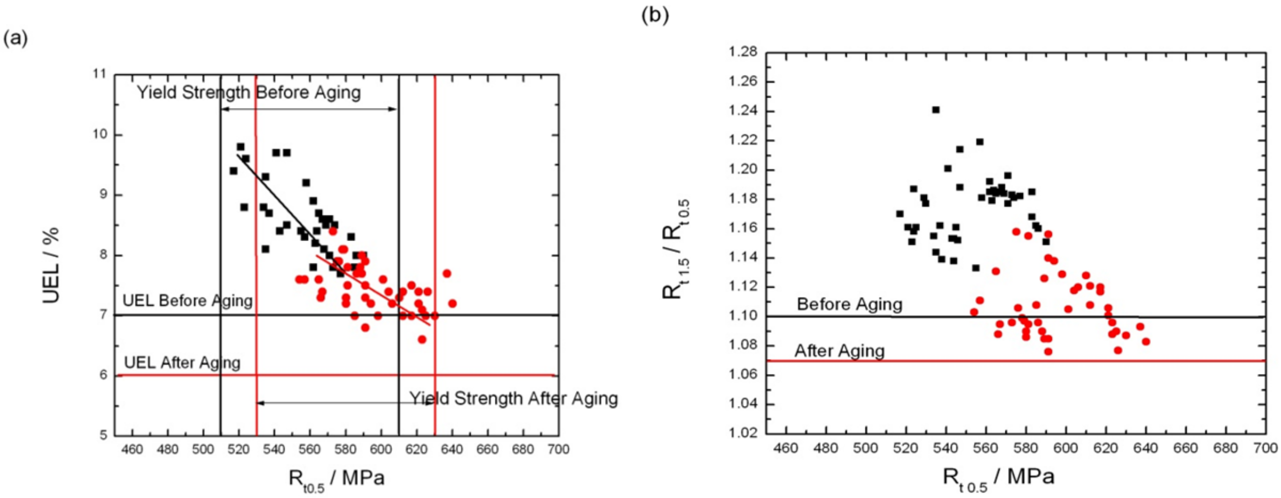

FIG. 3 STRAIN AGING BEHAVIOUR OF THE DEVELOPED X80 HIGH STRAIN PIPELINE. (A) LONGITUDINAL YIELD STRENGTH AND UEL TO $R_{T0.5}$, (B) $R_{T1.5}/R_{T0.5}$ TO $R_{T0.5}$

3 DISLOCATION AND PRECIPITATION HARDENING OF THE PRESENT DUAL PHASE X80 LINE PIPE STEEL

Effect of microstructure on stress-strain behaviour of dual phase steels were discussed in many researches, demonstrating great interest in second phases [1-2, 6-7, 10-15]. In fact, dislocation and precipitation hardening characterize the TMCP micro-alloyed steels [5]. However, quantitative study on the hardening effect by dislocation and precipitation steels for high strength line pipe manufacturing is seldom found in present papers.

3.1 Analysis on Dislocation Hardening

1) Positron Annihilation

In this study, it is found that high density dislocation characterizes microstructure of the pipeline steel, as shown in Fig. 1. The authors tried to analyse the hardening effect of dislocation by Positron Annihilation.

Positron Annihilation occurs mostly at vacancies where there is low density of dislocations and Positrons. The positrons will preferentially migrate into the vacancies after they are transmitted into the metal. Meanwhile, electronic energy at the vacancies is lower in comparison to where it is in relatively free-state. The annihilation radiated γ -ray energy will decrease, leading to narrow Doppler broadening spectrum and angular correlation curve. The increase of the Doppler broadening spectrum line parameters, peak numbers of the angular correlation curve and positron lifetime growth indicate the defects within the steel materials. Table 2 displays Positron Annihilation analysis results.

TABLE 2 POSITRON ANNIHILATION ANALYSIS RESULTS

τ_1(ns)	I_1(%)	τ_2(ns)	I_2(%)	τ_3(ns)	I_3(%)
0.07630	29.60	0.16350	68.40	1.240	2.008

where τ_1 is the Positron lifetime of small defect such as dislocations, ns; τ_2 is the Positron lifetime of large defect such as vacancy clusters, micro-cavities and micro-cracks etc., ns; I_i is the peak numbers of the angular correlation curve.

2) Calculation of Dislocation Density.

Definition of Positron trapping rate K by dislocation is according to the following equation (1) and the dislocation density ρ is calculated by the equation (2).

$$K=\mu\rho \tag{1}$$

$$\rho=K/\mu \tag{2}$$

where μ equals 0.725 cm^2/s for low carbon steels.

Definition of the average Positron lifetime is the following:

$$\bar{\tau}=(\tau_1-K)\frac{(1+K\tau_2)}{1+K(\tau_1-K)} \tag{3}$$

$$\bar{\tau}=\tau_1\times I_1+\tau_2\times I_2 \tag{4}$$

From equations (1) to (4), the dislocation density of the present pipeline steel is $3.62\times10^{14}m^{-2}$.

Calculation of Dislocation Hardening.

Dislocation hardening σ_d is calculated by equation (5) [14].

$$\sigma_d=M\alpha\mu b\rho^{1/2} \tag{5}$$

in which M is the orientation factor, for Body-centered Cubic steel, M is 3.1; α is a ratio index as 0.15; μ ,the shear modulus, 8.026×10^4MPa; b, the Burgers Vector, 2.48×10^{-10} m . From above, dislocation hardening is approximately 176MPa in the present studied steel.

3.2 Precipitation Analysis on the Grade X80 High Strain Line Pipe Steel

Ferrite and bainite volume fraction, morphology and distribution play important roles in Grade X80 steel for high strain line pipe manufacturing [1, 3-4, 6-9]. It is believed that the second phase and the martensite-austenite constituent (MA) enable low Y/T and high deformability [1-4, 7-8,15]. The authors studied the distribution of the precipitates by

TEM. Electrolytic Chemical Phase Analysis (ECPA) and X-ray Small Angle Diffraction (X-ray SAD) were used to study the precipitation morphology and volume fraction.

1) Result of Electrolytic Chemical Phase Analysis and X-ray Small Angle diffraction.

Precipitates, including M(C,N), M3C, CaS, AlN, Cu characterized the precipitation in the studied Grade X80 steel. All the M3C precipitates are of Orthogonal structure. Fe0.854Mn0.057Ni0.049Cr0.040)3C characterises the M3C. Its mass fraction is 0.0147 %. Cu and the Niobium and Titanium carbonitride（M(C,N)）are Face-Centered Cubic structure(FCC), as shown in Table 3. The phase constitution of M(C, N) is Nb0.757Ti0.237Cr0.006) (C0.464N0.536) with mass fraction of 0.0621%. The mass fractions of CaS, AlN and Cu are respectively 0.0029%, 0.0003% and 0.2156%. Nearly 90% of Cu is precipitated into the metal due to the Cu solid solution in the metal being electrolytic. However, little Cr-precipitates were found due to its solid solution. Fig. 4 displays the fraction histogram of the precipitated particle size. Mass fraction of particles less than 5nm is 5.30%. The median size of the precipitate is 69.19nm. The precipitate average size proves to be 75.78nm.

TABLE 3. LATTICE CHARACTERISTICS OF THE PRECIPITATES

Precipitates	Cu	Nb(C,N)	Ti(C,N)	M_3C
Lattice constant /nm	a0=0.3615	a0=0.445-0.446	a0=0.428-0.429	a0=0.4523-0.4530 b0=0.5088-0.5080 c0=0.6743-0.6772
Crystal families	FCC	FCC	FCC	Orthogonal

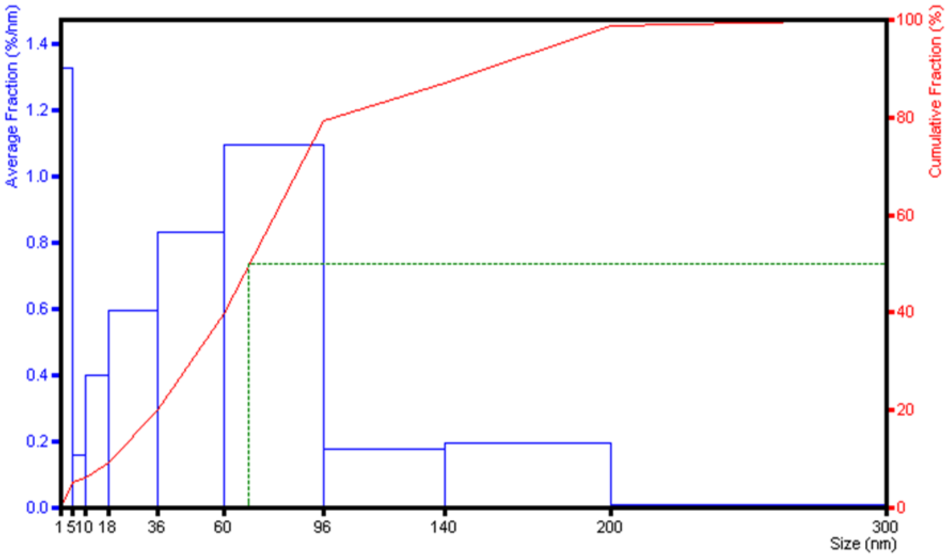

FIG. 4 THE PRECIPITATED PARTICLE SIZE MASS FRACTION

2) Precipitation Hardening

Equation (6) is applied to calculate the second phase particle strengthening according to Gladman and the Ashby-Orowan model.

$$\Delta\sigma_p = \frac{0.538 \cdot Gb \cdot f_v^{1/2}}{R} \ln\left(\frac{R}{2b}\right) \tag{6}$$

in which $\Delta\sigma_p$ is the yield strength increase (MPa); G is the Shear modulus, MPa, 81600MPa for Ferrite; b is the Burgers vector, 0.248nm for ferrite; f_V is the volume fraction of the precipitation particle that may be obtained by the mass fraction f_m, e.g. $f_V = f_m \times 7.87/7.803$; R is the diameter of the precipitation particle (mm).

Generally, carbon-nitride precipitated particles less than 20 nm have obvious precipitation strengthening effect. In this study, the carbon-nitride particle less than 20nm is considered when calculating the precipitation hardening, revealing a strengthening contribution of 58.1MPa.

4 CONCLUSIONS

In this paper, Grade X80 steel molybdenum and boron free for high strain line pipe steel manufacturing is characterized with ferrite and granular bainite. 1219mm outer diameter pipes were industrially manufactured by UOE process.

The mechanical properties and toughness of the pipe comply with the requirements of pipeline construction. Longitudinal $R_{t0.5}$ increases at an average of 42MPa while the UEL reduces 1.1% on average after aging. The stress ratio $R_{t1.5}/R_{t\,0.5}$ appears to have a reduction of 0.06. Dislocation strengthening appears to be 176MPa in the present studied steel. Characteristics of the precipitates were evaluated by both Electrolytic Chemical Phase Analysis and X-ray Small Angle diffraction. The median size of the precipitate is 69.19nm and the spread width is 48.63nm. The average size of the precipitate proves to be 75.78nm. Strengthening contribution by the precipitates less than 20nm in size is 58.1MPa.

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