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Experimental study on 830 MPa grade pipeline steel containing chromium

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Abstract: The diversity of microstructure and properties of 830 MPa grade pipeline steel containing chromium was investigated by optical microscope and transmission electron microscopy. The main microstructures were multiple configurations, containing lath bainite and granule bainite. Mechanical properties test results showed that the yield strength and tensile strength improved with increasing chromium content. The toughness and elongation decreased at the same time, so temper process was introduced. Appling proper temper parameters, the values of toughness and elongation were improved dramatically, and the strength decreased slightly.

Key words: chromium; high strength; pipeline steel; thermo-mechanical controlled process

1. Introduction

Pipeline transmission is the safest and the most economical method for transferring natural gas and petroleum [1-10]. Chinese government has paid much attention to pipeline construction. The planning projects will need 48,000 km pipes, which cost about 450-620 billion Yuan RMB.

At these present pipeline projects, the pipe is made of X70/X80 grade steel. In order to cut down the cost, X100/X120 grade steel is being developed, which can reduce about 5%-15% cost [11]. Due to high economic benefit, developed countries are quickly developing X100/X120 grade steel. Researchers in Japan and Europe have begun to explore X100/X120 in the early 1990s [12-13]. In 2003, ExxonMobil, cooperated with Sumitomo Metal Industries, developed X120 grade pipeline steel. In 2004, ExxonMobil, cooperated with Nippon Steel Corporation and Canada TCPL, constructed a 1.6 km X120 pipeline in the north of Alberta.

Modern pipeline technology for the production of oil and gas pipeline steels is aiming at achieving high strength and toughness. Some alloy additions such as Mo are very often added to achieve the satisfied microstructure and accordingly improve the strength [14]. Mo can enlarge the bainite transition region and enhance the strength of the plate obviously. Chromium (Cr), as the same as Mo belongs to group VI in the element periodic table, has similar character, which cooperates with Mo greatly retard pearlite transition. From a metallurgical point of view, optimal microstructure can be achieved through several metallurgical processes including a judicious selection of alloy additions, the optimized thermo-mechanical control process (TMCP), and a proper heat treatment processing [15]. The effects of Cr on the as-rolled and tempered 830 MPa grade pipeline steel were investigated in this article.

2. Materials and experimental methods

This test steel was smelted in a 200-kg vacuum induction furnace and cast steel ingots with dimensions of 120 mm×120 mm×470 mm. Its chemical composition is shown in Table 1. The ingots were reheated to 1200°C and then rolled to 18 mm test plates through TMCP, which were tempered in a chamber furnace at 500, 550, 600 and 650°C for 54, 90, 126 and 162 min, respectively.

After the temper, microstructures were observed by Olympus optical microscope and transmission electron microscopy (TEM). TEM samples were prepared by electrolysis thinning method. The precipitate was observed by TEM using carbon-film extraction. According to the standards of ASTM E32 and ASTM E370, the mechanical properties were examined on a ZJB-30B impact tester and a WAW-Y500 tensile testing system.

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Table 1. Chemical composition of the test steels wt%

No.	C	Si	Mn	P	S	Mo	Cr	Others
1#	0.043	0.24	1.88	0.010	0.005	0.25	0.18	Ni, Cu, Nb, Ti, B
2#	0.058	0.25	1.90	0.009	0.005	0.24	0.29	
3#	0.063	0.23	1.86	0.013	0.007	0.26	0.42	
4#	0.056	0.25	1.88	0.011	0.006	0.25	0.50	

3. Results and analyses

3.1. Mechanical properties of the as-rolled steels

The mechanical properties of the as-rolled steels are shown in Table 2. The yield strength and tensile strength increase with increasing Cr content. But the values of impact energy (−20°C) and elongation both show the converse trend. The properties of the as-rolled steel plates show high strength, low toughness, and low elongation.

Table 2. Mechanical properties of the as-rolled steels

No.	Thickness / mm	Yield strength, $R_{p0.2}$ / MPa	Tensile strength, R_m / MPa	Elongation, A / %	Impact energy (−20°C), A_{kv} / J
1#	18	845	1020	15	170, 158, 136
2#	18	890	1040	12	137, 134, 114
3#	18	960	1070	10	132, 116, 103
4#	18	985	1110	8	112, 109, 102

3.2. Mechanical properties of the tempered steels

Compared with the as-rolled steels, the tempered steels have higher elongation and toughness as shown in Fig. 1. With increasing Cr content, the difference of elongation between the as-rolled and tempered steels improved dramatically. The effect of temper process on the as-rolled steels (sample 2#) is shown in Fig. 2. The yield strength does not have a monotone trend among the whole range of temperature and time, at 550°C temper, the steels have the highest impact energy value. At 600°C temper, the steels have the lowest impact energy value and the highest yield value, as shown in Fig. 2(a). As observed in Fig. 2(b), the effect of time is small and the yield strength increases with increasing holding temperature.

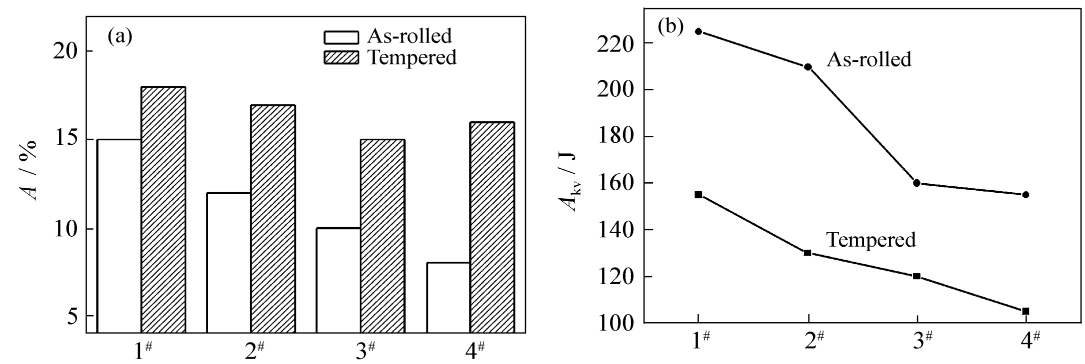

Fig. 1. Variation of elongation (a) and toughness (b) of the as-rolled and tempered steels.

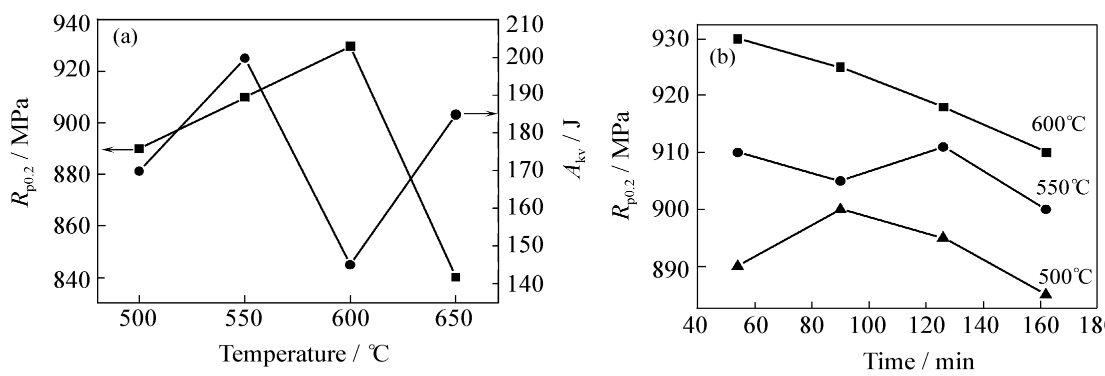

Fig. 2. Mechanical properties of the tempered steels at different temper parameters (2# steel): (a) temperature; (b) time.

3.3. Microstructure

The microstructure of the as-rolled steels consists of fine lath bainite and granule bainite, as observed in Fig. 3. The volume ratio of bainite increases with increasing Cr content gradually. Bainite laths cross the original austenite grains with different orientations and stagger each other. Cr and Mo are tend to combine with C, which can drag solute, decrease C diffusion coefficient, inhibit austenite-ferrite transition, and retard Fe_3C formation at high temperature [16].

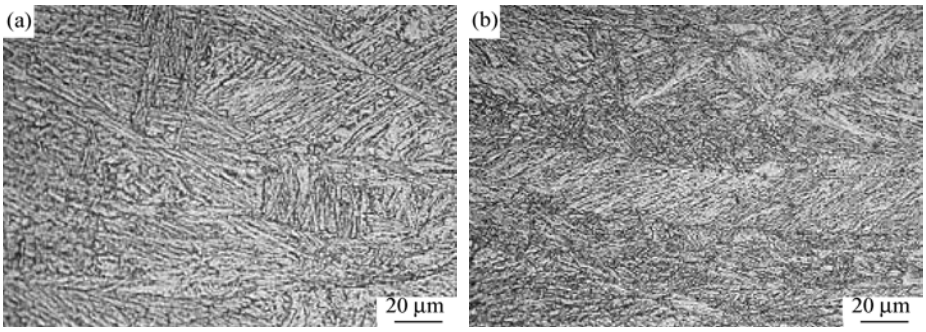

Fig. 3. Microstructures of the as-rolled steels with different Cr contents: (a) 0.18wt%; (b) 0.50wt%.

The microstructure of the as-rolled steel was observed by TEM as shown in Fig. 4. Several high-density dislocations and small quantity of martensite- austenite (MA) islands distribute in ferrite laths, as shown in Figs. 4(a)-4(b). MA has two effects [17]: (1) martensite is brittle phase and easy to form cracks; (2) residual austenite in MA is ductile phase and can absorb the energy of crack formation and propagation.

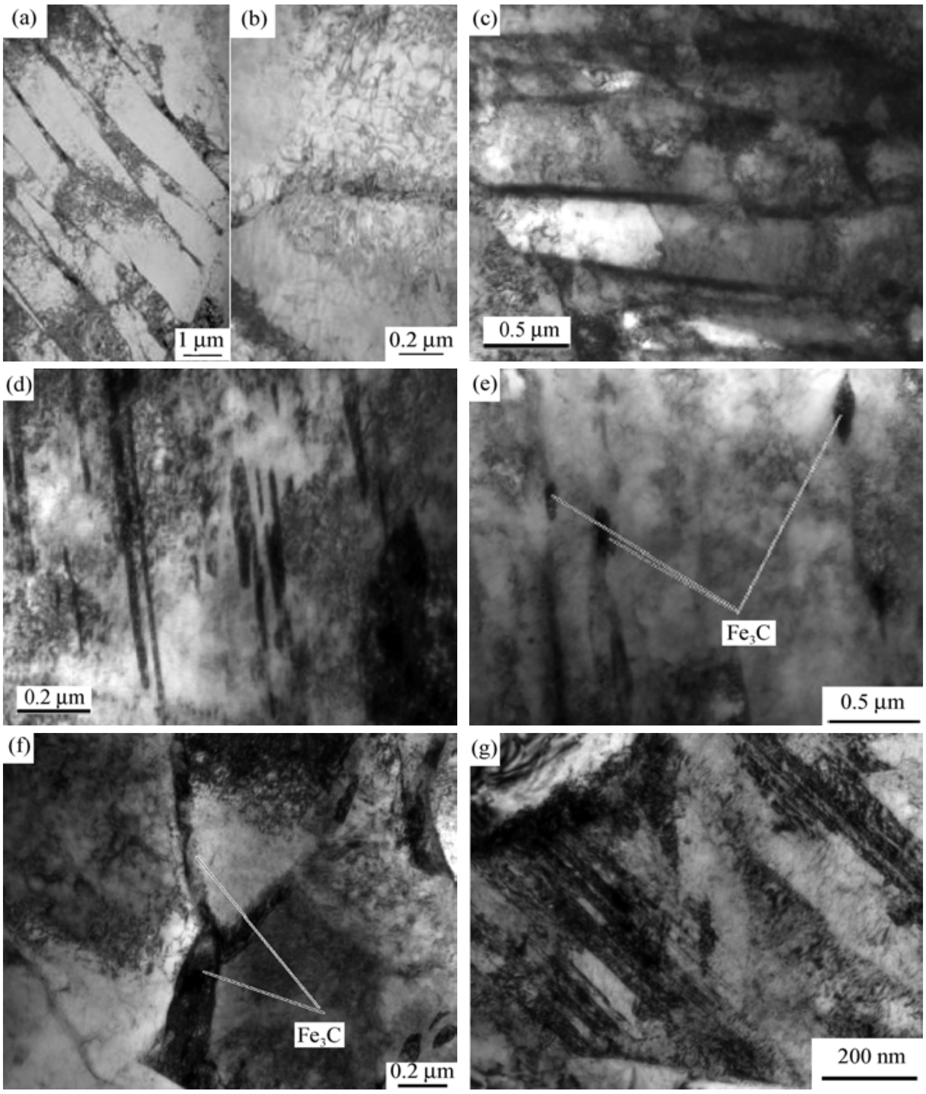

Fig. 4. TEM microstructures of the steel at the tempering time of 54 min with different tempering temperatures: (a) and (b) as-rolled; (c) 500°C; (d) and (e) 550°C; (f) 600°C; (g) 650°C.

The view of the authors is that fine MA dispersion can optimize the matching between strength and toughness. The ferrite lath character and the decrease in dislocation density are visible when tempering the as-rolled steels at 500°C and holding for 54 min, as shown in Fig. 4(c). When the temperature reaches 550°C, the ferrite lath character is still visible and Fe_3C precipitates begin to form in their lath boundary as shown in Fig. 4(d). When the temperature arrives at 600°C as shown in Fig. 4(e), ferrite initiates to revert and lath converts to polygon. MA began to decompose and the merged Fe_3C is obvious, as shown in Fig. 4(f). When the temperature reaches 650°C, the bainite laths are coarse, as shown in Fig. 4(g), which induce the strength to decrease greatly.

The diversity of precipitated phases was observed by TEM before tempering and after tempering, as shown in Fig. 5.

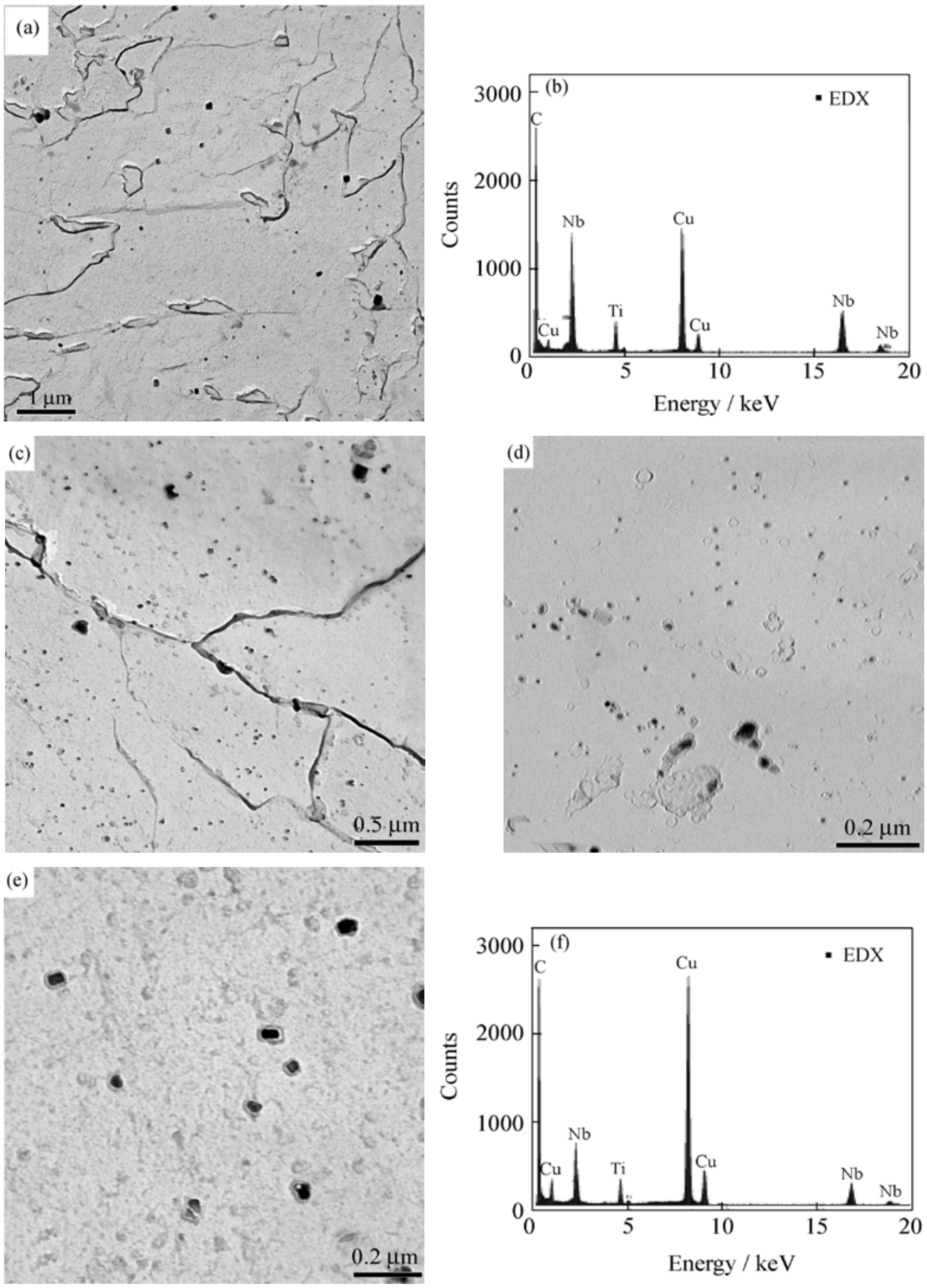

Fig. 5. Precipitation and spectra analysis for the as-rolled and tempered steels: (a) and (b) as-rolled; (c), (d), (e) and (f) tempered at 600°C.

Before tempering, their volume ratio is low and their size is 50-150 nm. Most of them are (Nb, Ti) (C, N) analyzed by energy spectrum analysis, as shown in Fig. 5(b). $3^{\#}$ and $4^{\#}$ samples were tempered at 600°C for 54 min, the volume ratio of the second phase is larger than that of the as-rolled steels as shown in Figs. 5(c) and 5(d). For $1^{\#}$ and $2^{\#}$ samples, the second phase size and volume ratio are not changed apparently before or after tempering as shown in Figs. 5(e) and 5(f). The conclusion is that: 0.4wt% Cr or more can enhance the strength for promoting the fine precipitation after tempering at 550-600°C; and 0.3wt% Cr or less can also improve the strength because dissolved Cr in the base can cause an extra elastic strain field for the lattice distortion. Both can inhibit dislocation movement and enhance the strength of the base material.

4. Conclusion

The addition of Cr supports the combination of proper microstructure and good mechanical properties. With TMCP and temper process, the experimental plates satisfy the need of X120 grade pipeline steel. The microstructure consists of fine lath bainite and granule bainite. There are high-density dislocations in the bainite lath and partial dislocations are nailed by fine precipitates. The values of impact energy and elongation of the tempered samples increase obviously, compared with those of the as-rolled steels, and the strength decreases only slightly.

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