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Development of Ultra-High Strength Linepipes with Dual-Phase Microstructure for High Strain Application†

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Abstract:

Extensive studies have been conducted to develop high strength linepipes with higher deformability. One of the key technologies for improving deformability is dual-phase microstructural control. Steel plate with ferrite-bainite microstructure can be obtained by applying thermo-mechanical controlled processing (TMCP), a process of controlled rolling and accelerated cooling. Low carbon, boron-free steels were used to enable the ferrite formation during cooling after controlled rolling, and accelerated cooling with an ultimate cooling rate enhanced the strength up to the X120 grade. HOP® (Heat-treatment On-line Process) was also applied after accelerated cooling in order to improve the Charpy energy of the base material. Trial production of X120 high deformability linepipe was conducted by applying dual-phase microstructural control. Microstructural and mechanical properties of X120 linepipe are introduced in this paper.

1. Introduction

There has recently been a growing demand for higher grade linepipes that can help reduce the total cost of long-distance pipelines. The application of high-strength linepipes such as API X70 and X80 grades has therefore been increasing in recent years, and the X100 grade was put to practical use for the first time in 2002[1)]. Developments have been also conducted on X120 linepipes. On the other hand, pipeline developments have been expanded toward environmentally severe regions such as permafrost and seismic regions. The linepipes installed in these regions, where ground movements can be expected to impose larger strains, must have deformability sufficient to prevent local buckling and girth weld fracture.

Thermo-mechanical controlled processing (TMCP), a process of controlled rolling and accelerated cooling, is applied for producing high strength linepipe steels. Fine bainitic microstructures obtained by accelerated cooling confer a good balance of high strength and toughness. In order to increase the strength to X120 grade, a lower bainite microstructure obtained by the addition of boron is applied[2,3)]. It becomes difficult, however, to balance high strength and high deformability in steel with a single bainitic microstructure. Deformability of linepipe is strongly affected by microstructure of the steel. Steels with a dual-phase microstructure are well known to exhibit higher strain hardenability and superior deformability[4)]. By applying ferrite-bainite microstructural control, high-deformability linepipes of up to grade X100 have been developed[5)].

In this paper, design concept for improving deformability while balancing high strength and toughness of the base material of ultra-high strength linepipes are introduced from the metallurgical point of view. Trial production results of high deformability X120 linepipes are also presented.

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2. Dual-Phase Microstructural Control for X100 and X120 Linepipe

2.1 Effects of Plate Rolling Conditions on Microstructure

The production of a ferrite-bainite dual-phase microstructure by TMCP requires precise temperature control during the plate rolling. Therefore, the effect of accelerated cooling conditions on the microstructure was investigated by conducting a laboratory plate-rolling test on steel with a chemistry of 0.08C-0.25Si-1.5Mn-0.04Nb. After the steel plates were hot rolled, accelerated cooling was applied at different temperatures. **Figure 1** shows the effect of the accelerated cooling starting temperature on the bainite volume fraction. The accelerated cooling starting temperature is expressed as the temperature subtracted by the Ar_3 temperature, the ferrite transformation starting temperature, under continuous cooling.

Bainite volume fraction was 100% when the accelerated cooling starting temperature was above the Ar_3 temperature, and it decreased as the accelerated cooling starting temperature fell below the Ar_3 temperature. **Figure 2** shows the relation between uniform elongation and the bainite volume fraction. The highest uniform elongation was obtained by steel with a bainite volume fraction of around 50%.

According to the experimental and analytical studies on the effect of the microstructure on deformation behavior of ferrite-bainite steel, Y/T ratio or n-value was strongly influenced by the bainite volume fraction, as well as the strength difference between the soft phase and hard phase. Therefore, it can be assumed that the optimum bainite volume fraction depends on the chemistry and plate manufacturing conditions. It can also be concluded that it is very important to optimize the microstructure by precise control during the plate manufacturing process, in order to produce high-deformability linepipes.

2.2 Effect of Boron on Transformation Behavior

Boron is a useful element to increase strength with a relatively lower chemistry. However, dual-phase microstructural control becomes very difficult in boron-added steels. **Figure 3** shows continuous cooling transformation (CCT) diagrams for boron-free and boron-added steels. Ferrite forms in the boron-free steel during slow cooling at around 700°C, whereas ferrite formation is almost wholly absent in the boron-added steel. Another difference between the CCT diagrams is a lower bainite transformation temperature for the boron-added steel. This addition of boron apparently promotes the transfor-

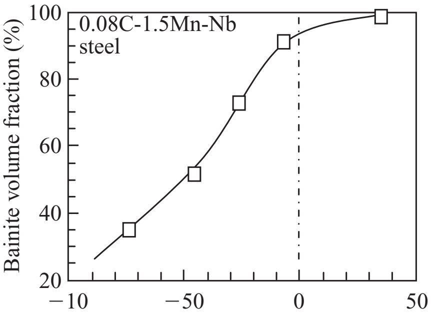


Fig. 1 Effect of accelerated cooling starting temperature on bainite volume fraction

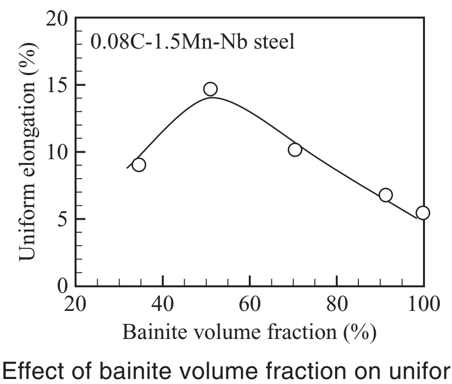
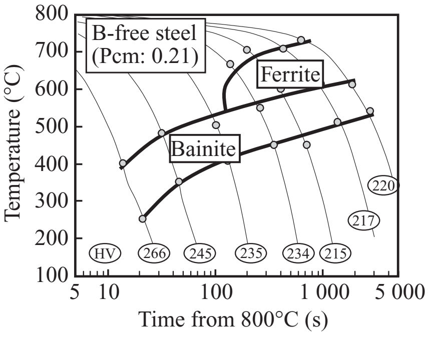
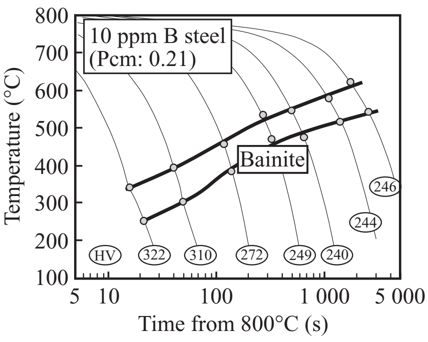


Fig. 2 Effect of bainite volume fraction on uniform elongation



(a) 0.07C-1.9Mn-0.3Mo-Cu-Ni-0.04Nb



(b) 0.05C-1.9Mn-0.3Mo-Cu-Ni-0.04Nb-0.001B

Fig. 3 Continuous cooling transformation (CCT) diagrams of (a) Boron free and (b) Boron added steels mation of lower bainite, and this confers a large benefit in obtaining high strength. It is impossible, however, to obtain a ferrite-bainite dual-phase microstructure using boron-added steel. Thus, the use of boron-free steel is recommended for producing high-deformability linepipe material.

2.3 Effect of Microstructure on Strength-Deformability Balances

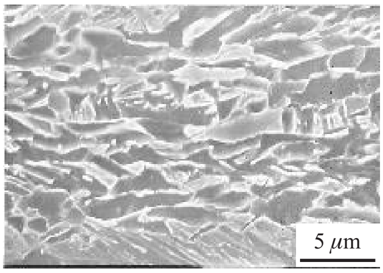
To investigate the effects of microstructure on strength and deformability, two series of laboratory plates, were prepared one with a boron-added bainite microstructure and the other with a boron-free ferrite bainite microstructure, with tensile strengths of up to 1 000 MPa. **Table 1** shows the chemical compositions of the steels for the laboratory test. Plates with a thickness of 15.0 mm were manufactured by controlled rolling followed by accelerated cooling using laboratory equipment. **Photo 1** shows the typical microstructure for both types of steel plate. The accelerated-cooling-stop temperature was controlled to form a ferrite-bainite microstructure for the boron-free steel (Fig. 1), while the boron-added steel showed a single bainitic microstructure. **Figure 4** shows the stress-strain curves for the two steels in the longitudinal direction of the plates. The differences in microstructure lead to considerable differences in the stress-strain curves. The high strength of X120 grade is achieved for both steel plates, but uniform elongation is much longer for the boron-free steel, the steel with the ferrite-bainite microstructure.

The relation between the tensile strength and uniform elongation is shown in **Fig. 5**. The ferrite-bainite boron-free steel clearly exhibits a higher uniform elongation than the boron-added steel. Similarly, the *Y*/*T* ratios of the two steels also differ. **Figure 6** shows the relation between the tensile strength and *Y*/*T* in the longitudinal direction. The ferrite-bainite dual-phase steel shows a

Table 1 Chemical compositions of the steel plates used for laboratory test

Type	C	Si	Mn	Mo	others	Pcm*
Boron added	0.05	0.10	1.9	0.30	Cu, Ni, Nb, V, Ca, B	0.20–0.21
Boron free	0.07	0.10	1.8–1.9	0.2–0.3	Cu, Ni, Nb, V, Ca	0.19–0.22

* Pcm = C+Si/30+(Mn+Cu+Cr)/20+Mo/15+Ni/60+V/10+5B



(a) Boron free (Pcm: 0.21)

(b) Boron added (Pcm: 0.21)

Photo 1 Microstructure of boron free and boron added steels

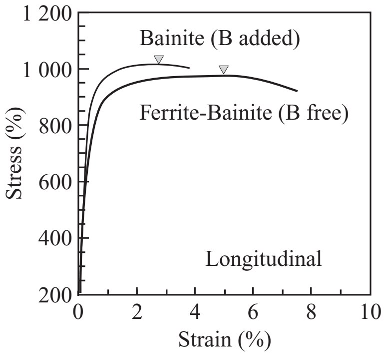


Fig. 4 Longitudinal stress-strain curves

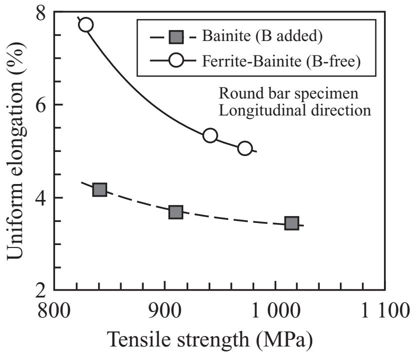


Fig. 5 Relation between uniform elongation and tensile strength for bainite steel and ferrite-bainite steels

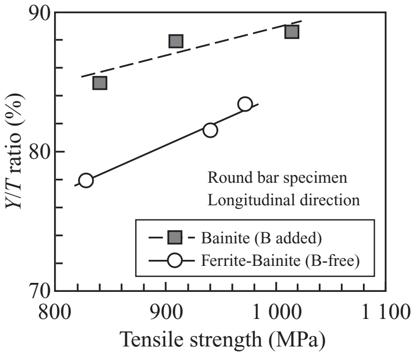


Fig. 6 Relation between *Y*/*T* ratio and tensile strength for bainite steel and ferrite-bainite steels

lower *Y*/*T* ratio even in higher strength regions. Therefore, dual-phase microstructural control is essential measure for balancing high strength and deformability, especially for X120 grade linepipe steel.

2.4 Effect of On-Line Heat Treatment on the Charpy Energy of the Ferrite-Bainite Steel

Charpy absorbed energy is required for the prevention of running ductile fractures. A lower rolling finishing temperature, i.e., a lower accelerated cooling starting temperature, has been reported to bring about a lower Charpy energy[6]. This makes it difficult to achieve higher Charpy energy for the steels with dual-phase microstructure which needs lower accelerated cooling start temperature. In this study, HOP®(Heat-treatment On-line Process) was investigated as a means to improve Charpy energy of high strength linepipe[7]. **Figure 7** shows a schematic temperature profile of the plate manufacturing process. In the conventional TMCP process, the steel plate is controlled rolled, accelerated cooled, and then cooled in air. In the HOP applied process, the plate is rapidly heated by induction coils immediately after the accelerated cooling. HOP offers several advantages in the production of high performance linepipe materials. One of the benefits of applying HOP is recovery of the dislocation density introduced by the bainite transformation during the accelerated cooling.

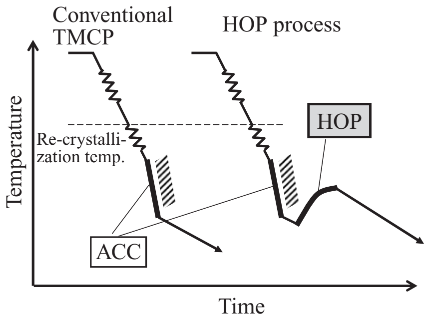


Fig. 7 Schematic temperature profiles in plate production process

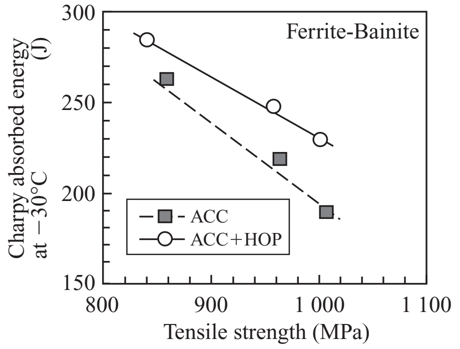


Fig. 8 Relation between Charpy energy and tensile strength for ferrite-bainite steels

Figure 8 shows the relation between Charpy energy and tensile strength of ferrite-bainite steels produced with accelerated cooling (ACC) and with heat treatment after accelerated cooling (ACC+HOP). Heat treatment was applied after the accelerated cooling by laboratory equipment. Higher tensile strengths led to large drops in the Charpy energy in both steels, but higher Charpy energy was obtained by applying HOP heating. The heating temperature was carefully controlled to get dislocation recovery only, and no significant changes in tensile properties such as yield strength or tensile strength were seen after HOP heating.

3. Trial Production of X120 Linepipe

3.1 Chemistry and Manufacturing Conditions for X120 Linepipe

Based on the above investigations on the balancing of high strength and deformability, trial production of X120 linepipe with improved deformability was conducted. **Table 2** shows chemical compositions of trial X120 linepipe. Pcm was kept to a low value in order to maintain good weldability. Steel plates with a thickness of 19.0 mm were produced by applying accelerated cooling followed by HOP (heat treatment on-line process). Plate manufacturing parameters such as the rolling finishing temperature, accelerated cooling stoping temperature, and on-line heat treatment temperature were carefully controlled in order to balance high strength, high deformability, and other material properties. Finally, pipes with the diameter of 914.4 mm were produced by the UOE process.

3.2 Mechanical Properties of Trial X120 Linepipe

The mechanical properties of the trial X120 linepipes are shown in **Table 3**. Adequate transverse tensile strength was achieved. The most significant characteristics of this trial X120 linepipe were a higher uniform elongation and lower *Y*/*T* ratio in the longitudinal direction. **Figure 9** shows an example of the longitudinal stress-strain curve of the trial X120 linepipe. Although the deformability of the X120 linepipe should be tested by conducting full scale bending tests, larger strain capacity can be expected for strain-based design. DWTT

Table 2 Chemical compositions of X120 linepipe

(mass%)

C	Si	Mn	Mo		Pcm
0.06	0.15	1.91	0.27	others	0.22

* Pcm = C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10 +5B

Table 3 Mechanical properties of trial X120 linepipe

Pipe number	Tensile test									Trans-weld
	Transverse				Longitudinal					
	YS (MPa)	TS (MPa)	*Y*/*T* (%)	El (%)	YS (MPa)	TS (MPa)	*Y*/*T* (%)	El (%)	uEl (%)	TS (MPa)
1	906	934	97	18	750	920	82	29	4.0	932
2	840	958	88	19	743	963	77	30	4.8	952

YS: Yield strength TS: Tensile stress *Y*/*T*: Yield ratio
El: Elongation uEl: Uniform elongation

Pipe number	Charpy test			DWTT properties		
	vE at −30°C			SA at −20°C (J)		85% SATT (°C)
	Base metal	HAZ	Weld metal			
1	263	119	65	86	91	−25
2	211	77	60	89	83	−22

DWTT: Drop weight tear test

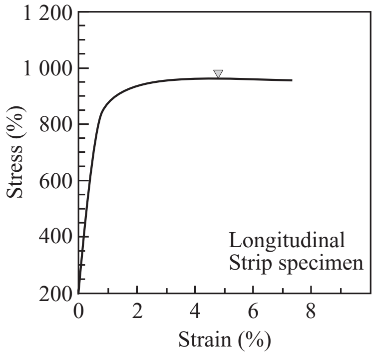


Fig. 9 Longitudinal stress-strain curve of trial X120 linepipe

test results demonstrate that a design temperature of −20°C can be applied for this pipe.

3.3 Microstructural Characteristics

The microstructure of the trial X120 linepipe is shown in **Photo 2**. The ferrite phase is fine and polygonal, with an adequate volume fraction. Thus, higher uniform elongation and lower *Y*/*T* were obtained.

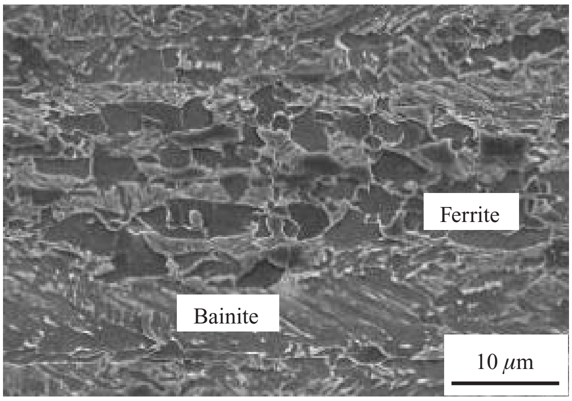


Photo 2 SEM micrograph of X120 linepipe

4. Conclusion

Ultra-high-strength linepipe with excellent deformability was developed by ferrite-bainite dual-phase microstructural control. Trail production of X120 UOE linepipe of 914.4 mmOD × 19.0 mmWT was conducted. The trial X120 linepipe exhibited high strength, superior deformability with uniform elongation in the longitudinal direction of above 4%, and *Y*/*T* ratio of 85%. Excellent DWTT toughness was also achieved at −20°C design temperature.

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