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Development of API X80 Grade Electric Resistance Welding Line Pipe with Excellent Low Temperature Toughness†

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Abstract:

This paper introduces nature and characteristics of the X80 electric resistance welding (ERW) line pipe. Thick-walled high strength line pipes are to be increasingly used for high pressure pipeline operation to improve the transport efficiency for natural gas and oil. To improve the material properties of hot coil for X80, the effects of microstructure, chemical composition on strength and toughness were investigated. Based on the result, JFE Steel has developed ultra low carbon bainitic ferrite steel with fine precipitates and no coarse pearlite or martensite by applying JFE Steel's thermomechanical controlled process (TMCP) technologies. Good balance of material properties of base material and seam weld suitable for low temperature use was obtained.

1. Introduction

Thick-walled high strength line pipes are being increasingly used for high-pressure pipeline operations to improve the transport efficiency for natural gas and oil. Thicker line pipes with higher yield strengths are necessary for this purpose. This presents a problem, however, as line pipes with higher strength, such as the API X80 grade, have lower fracture toughness. As an added challenge, line pipe construction for natural gas and oil transport is taking place in severe environments such as the arctic region. Thus, the line pipe must have low-temperature toughness, together with the high tensile properties.

To provide high tensile properties with low-temperature toughness, the plate-UOE pipe process has been used to manufacture higher grade and thick-walled X80 grade line pipes[1–3]. The bainite single phase which is transformed at very low temperature with ultra-low carbon steels improves the toughness by keeping the hard, coarse secondary phase away. As an alternative approach, Kim et al. studied the manufacture of X80 line pipe steel with a bainitic microstructure achieved by a low stop-cooling temperature using electric resistance welding (ERW) with hot-rolled sheets[4]. Though the ERW process had higher production rates, the coiling, an in indispensable process, made it difficult to obtain a bainite microstructure with good toughness. **Figure 1** shows the ERW production process. In hot rolling, stop-cooling is generally necessary before coiling at 500 to 700°C. The stop-cooling temperature of the hot-rolled

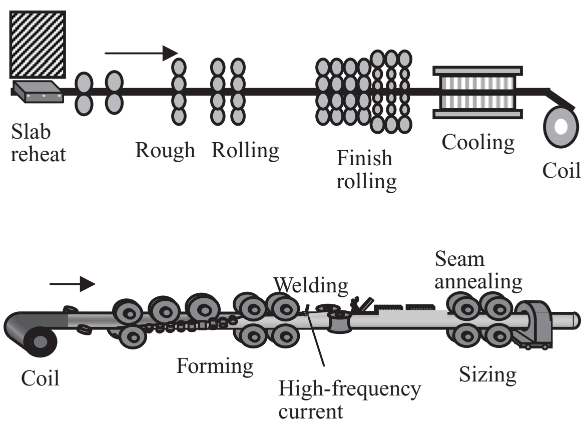

Fig. 1 Hot rolling-ERW pipe manufacturing process

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sheet is much higher than that of plate (less than 350°C). It was therefore difficult to obtain good toughness with a lower bainite microstructure identical to the microstructure of the plate-UOE pipes processed by ERW.

In this paper the authors describe investigations to resolve the above issue and develop a new microstructure for X-80 ERW line pipes with a precipitation-hardened bainitic ferrite microstructure and a low Pcm value for good weldability.

2. Design Concept

To improve the low-temperature toughness of the pipe, the performance of the steel sheet, the mother material of the pipe, should be improved. For ERW pipes, the toughness of the base material and the weld has to be ensured simultaneously. The weld has the same chemical composition as the base material. In the first part of this study the authors sought to determine how the chemical composition and microstructure of the steel sheet affected the toughness. Generally speaking, an increase of alloying elements degrades toughness. The results revealed that the higher carbon equivalent of the base material degraded the toughness of the weld due to the hardenability. Higher carbon equivalent and weld toughness were in good agreement. Moreover, a higher absolute carbon content degraded the toughness of the base material via the precipitation of the coarse carbides. The performance of the base material also depends on the microstructure. **Figure 2** is a schematic drawing of crack propagation of line pipe steel. The grain refinement and deduction of coarse polygonal ferrite and carbide are thought to be efficient enough to avoid crack propagation.

As described in the first paragraph, the ERW pipe material has to be coiled for the production of line pipe. Therefore, we studied to optimize the chemical composition and the sheet manufacturing condition. The stop-cooling temperature in the heat cycle is within nearly the same temperature range of precipitation hardening, and sheet coil is cooled very slowly after coiling. This temperature is suitable for precipitation hardening by the addition of micro-alloyed element such as Nb and V to confer strength, but the temperature range tends to promote the precipitation of hard secondary phase and ferrite grain growth In search of a countermeasure, the authors investigated two approaches:

(1) Reduce carbon to an extremely low level, to reduce hard secondary phases such as pearlite and martensite
(2) Avoid the precipitation of coarse ferrite and pearlite during cooling

Through these approaches, we achieved an extra-low-carbon steel with a single phase of fine bainitic ferrite microstructure with almost no coarse carbides suitable for our purpose. Next, we investigated how we could obtain a bainitic ferrite microstructure with extra-low carbon steel during hot rolling. We found that the addition of the elements for hardenability, such as Mn, Cu, Mo, effectively reduced the ferrite transformation temperature and slowed the pearlite transformation. A thermo-mechanically controlled process (TMCP) of controlled rolling and accelerated cooling during hot rolling also applied with a minimal carbon equivalent in the chemical composition for good weldability and weld toughness.

3. Effect of the Carbon Content on the Microstructure of the Material

3.1 Experimental Procedure

The chemical compositions of the steels used are shown in **Table 1**. Steel A was a conventional low-carbon X80 grade steel for warm environments. Steel B was an extra-low-carbon steel designed as X80 for low temperature use, as described above. Steel B was examined by drawing a continuous cooling transformation (CCT) diagram to find the cooling condition required to obtain a bainitic ferrite microstructure. **Figure 3(**a) illustrates the heat cycle of the CCT test. Samples were strained at 800°C before cooling to substitute the effect of finish rolling. Laboratory hot rolling with a coiling cycle was carried out to test how the reduced carbon content influenced the microstructure. Steels A and B were hot rolled, held in the furnace at the coiling temperature of about 600°C, and micro-structurally examined. The heat cycle of laboratory rolling is shown in Fig. 3(b). The effect of the coiling temperature on the tensile properties of Steel B was also examined.

Photo 1 shows the microstructure hot rolled sheet of

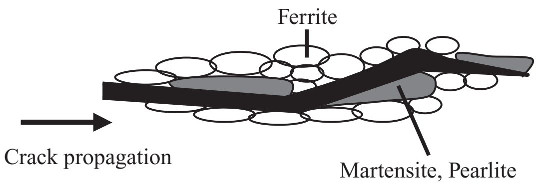


Fig. 2 Schematic drawing of crack propagationof line pipe

Table 1 Chemical Composition of the steel used

(mass%)

Steel	C	Si	Mn	P	S	Nb	Others	Pcm
A	0.06	0.25	1.62	0.01	0.003	0.05	V, Ti, Mo	0.16
B	0.03	0.23	1.62	0.014	0.002	0.05	V, Ti, Cu, Ni, Mo	0.15

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

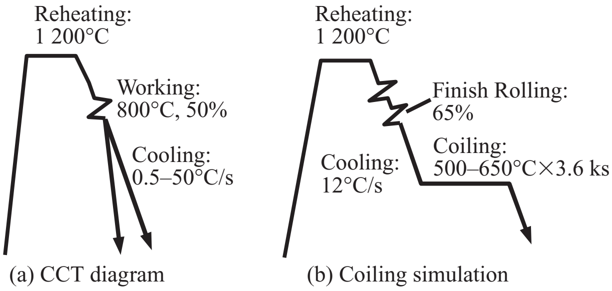


Fig. 3 Heat cycle

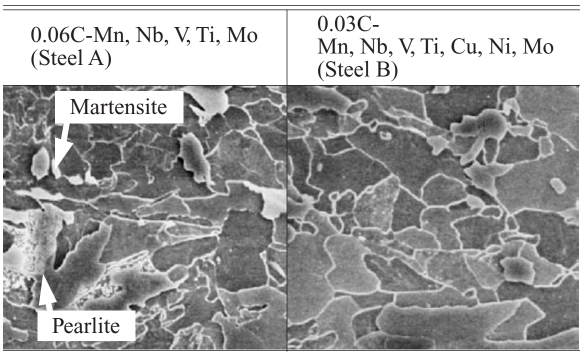


Photo 1 Effect of carbon on the microstructure

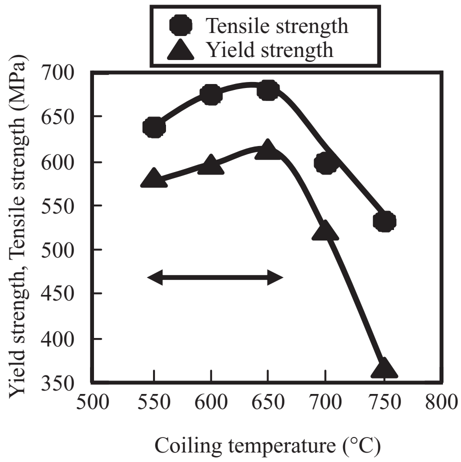


Fig. 4 Effect of coiling temperature on the strength

steel A and B after the coiling cycle. The microstructure of Steel A, 0.06%C steel, contained large pearlite and martensite. The microstructure of Steel B, 0.03%C steel, was bainitic ferrite with no pearlite or martensite. This result showed that bainitic ferrite single phase could be obtained as hot rolled.

The effect of coiling temperature on strength of steel B showed in **Fig. 4**. Bainitic ferrite microstructure was obtained in the range of 500 to 650 °C of coiling temperature and the yield and tensile strength (YS, TS) satisfied the X80 specifications.

3.2 Results

The transformation behavior is shown in **Fig. 5**. The bainitic ferrite transformation start temperature was

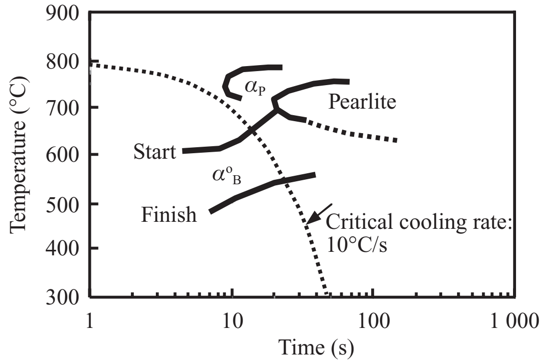


Fig. 5 CCT diagram of steel B

near 600°C, and the critical cooling rate was 10°C/s, an ordinary cooling rate on a hot runout cooling table for line pipe steel. Polygonal ferrite transformed at a higher temperature than the bainitic ferrite, and the pearlite transformation temperature was above 600°C when the cooling rate was less than the critical cooling rate. The polygonal ferrite and pearlite were relatively coarse, as their transformation temperatures were higher than that of the bainitic ferrite. The authors thus found that the bainitic ferrite microstructure in use for extra-low carbon steel could be obtained during hot rolling when the stop-cooling was carried out under 600°C.

3.3 Discussion

To estimate the amount of precipitation, **Fig. 6** shows the amount of precipitated Nb measured by the dissolution extraction method. At coiling temperatures of 600 and 650°C, the strength and precipitated Nb rose. The abundant fine Nb carbonitrides presumably precipitated. If the coiling temperature was 700°C or above, the ferrite grain and Nb precipitates coarsened and the yield and tensile strength decreased. At a coiling temperature of 550°C or below, the precipitated Nb was scanty. Yet with the dissolution method, some amount of fine precipitates might be omitted. Thus, the authors assumed that fine precipitation would occur.

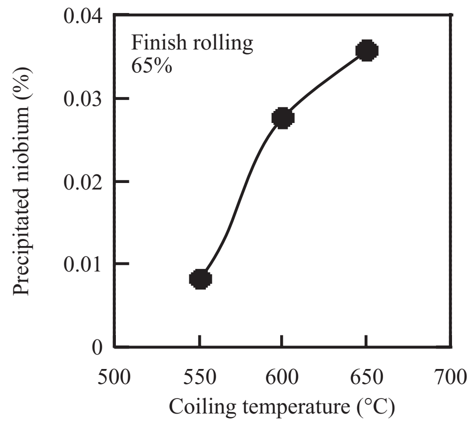


Fig. 6 Precipitated niobium amount (0.05% Nb steel)

As a result, a bainitic ferrite microstructure with apparently excellent low-temperature toughness with Nb precipitation hardening could be obtained at a coiling temperature of 500 to 650°C.

4. Mechanical Properties

4.1 Pipe Production

X80 ERW line pipes with a wall thickness of 16 mm were manufactured. The chemical composition of the steel was practically equivalent to that of Steel B shown in Table 1. The steel sheet coil was rolled from a 215 mm-thick slab with a finish rolling ratio of more than 65%. The coiling temperature was above 500°C. ERW pipes were produced from the hot-rolled coil, and the weld seam portion was annealed just after high-frequency welding above Ac3 temperature.

4.2 Evaluation of Material Properties

Figure 7 shows the tensile properties of the pipe in the transverse direction. The rectangle in this figure denote specifications for API X80. The strengths measured satisfied the specifications. **Figure 8** shows the Charpy impact test results with a full-sized V-notched specimen. The results were adequate. The absorbed energy of the pipe body was more than 300 J down to a temperature of −60°C. The weld seam was also fractured, in an almost ductile manner, down to a temperature of −60°C. DWTT SATT of the pipe body was below −20°C.

Table 2 showed the girth-welding test results. The heat input was settled 12 kJ/cm in consideration of welding efficiency. The welding resulted in success, the girth welded joint had sufficient tensile strength and fractured in base metal.

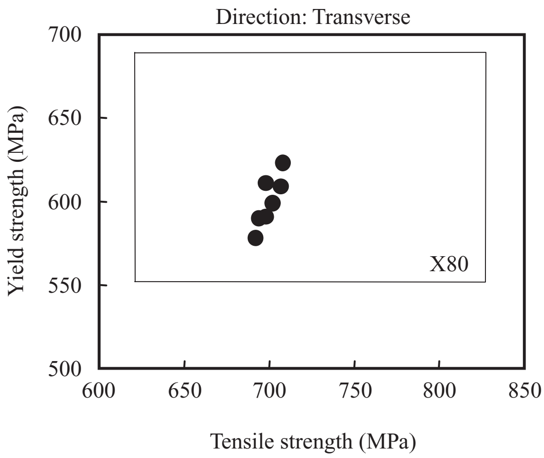


Fig. 7 Tensile properties of X80 pipes

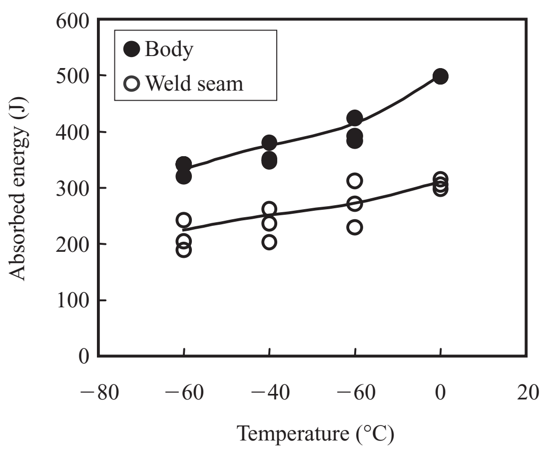
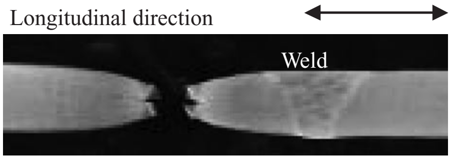


Fig. 8 Results of the Charpy V-notch test

Table 2 Girth welding test results

Welding procedure	Welding wire (Filler)	Strength of weld metal	Heat input (Average)
SMAW: 9 pass	low H 100 ksi (690 MPa)	overmatch	12 kJ/cm

Tensile test result



Tensile strength: 697 MPa
Fracture: Base metal

4.3 Discussion

Photo 2 shows the microstructure of the pipe body and seam. The body has fully bainitic ferrite microstructure, with no coarse pearlite or martensite. The seam also consists of almost an entirely bainitic ferrite, and scanty cementite and martensite. The authors assumed that the heat input of seam weld dissolved carbides only minimally, as the steel had an extremely low carbon content together with adequate X80 strength.

The strength of the line pipes was ensured, presumably because the microstructure consisted of a fully bainitic ferrite phase and only scanty high-temperature phases such as pearlite or coarse polygonal ferrite.

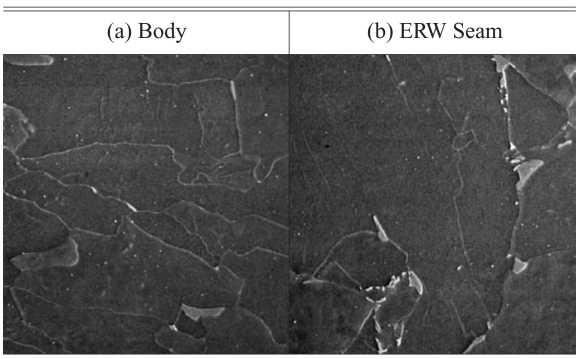


Photo 2 Microstructure of ERW pipe

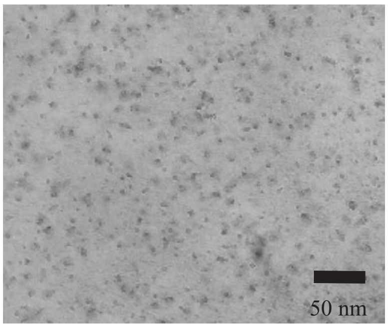


Photo 3 TEM micrograph of ERW body

Moreover, fine Nb precipitates were dispersed in the bainitic ferrite phase. **Photo 3** shows a TEM micrograph of the large amount of fine dispersed precipitates, a condition that seemed effective for precipitation hardening in the pipe body.

The Charpy absorbed energy was greater then 300 J. The large energy value also seemed to be related to the uniform microstructure. That is, the decreases of coarse secondary phases such as pearlite and martensite, phases that compromise low-temperature toughness, led to a decrease in crack propagation paths.

5. Conclusions

(1) The reduction of carbon content to an extremely low level resulted in excellent low-temperature toughness.

(2) The application of the new microstructure concept with precipitation-hardened bainitic ferrite enabled the production of pipes by a hot strip and ERW process. The mechanical properties were favorable.

(3) An X80 grade strength and excellent low-temperature toughness of the base material and weld were achieved. The toughness value of vTrs was below −50°C for each weld and base material.

(4) This material also has good weldability for girth welding because of the low Pcm value.

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