JFE TECHNICAL REPORT
No. 18 (Mar. 2013)

API X80 Grade Electric Resistance Welded Pipe with Excellent Low Temperature Toughness†

NAKATA Hiroshi[*1] KAMI Chikara[*2] MATSUO Nobuyuki[*3]

Abstract:

This paper introduces nature and characteristics of the API X80 high frequency electric resistance welded (HFW) pipe. Thick-walled high strength line pipes are to be increasingly used for high pressure pipeline operation to improve the transportation 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 this study, JFE Steel has developed low carbon bainitic ferrite steel with fine precipitates and no coarse pearlite and 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 steel line pipes have been applied in response to the increasing need for high pressure operation in recent years in order to achieve higher efficiency in energy transportation by pipelines. However, because toughness deteriorates due to the increased content of alloying elements, particularly in high strength grade steels such as API X80 (API: The American Petroleum Institute), it is difficult to secure the toughness of the base material and the weld simultaneously when low temperature toughness at −20°C and lower is required. For this reason, it is difficult to apply this material to natural gas transportation pipes and cold climates.

To overcome this problem, UOE steel pipes using steel plates as the starting material have been developed, for example, bainitic steel produced by accelerated cooling technology using low carbon equivalent steel[1–4].

In developing high toughness line pipe products covering comparatively small-diameter sizes with outer diameters of 26" (660 mm) and less, JFE Steel conducted a review of the steel composition and study of the hot rolling manufacturing conditions from the viewpoint of reducing factors in the microstructure of the steel coils used as the starting material which deteriorate toughness, with the aim of applying the high frequency electric resistance welded (HFW) pipe process using hot coils as the starting material. This paper introduces X80 grade HFW pipe with excellent low temperature toughness, which was commercialized by microstructure improvement by the reduction effect of C contents, active use of precipitation strengthening by micro-alloy elements, and application of microstructure control by hot rolling.

2. Concept of Material Design

2.1 Target Properties of Pipe

The development targets for the new X80 grade HFW pipe were as follows: (1) Base material: 85% SATT ≦ −20°C in DWTT (SATT: Shear area transition temperature, DWTT: Drop weight tear test), Charpy transition temperature vTrs ≦ −60°C, (2) Weld Charpy transition temperature vTrs ≦ −46°C, and (3) Suitability for girth welding and no fracture of the heat affected zone (HAZ).

† Originally published in *JFE GIHO* No. 29 (Feb. 2012), p. 11–16

*2 Senior Researcher General Manager,
Sheet Products Res. Dept.,
Steel Res. Lab.,
JFE Steel

*1 Senior Researcher Deputy Manager,
Sheet Products Res. Dept.,
Steel Res. Lab.,
JFE Steel

*3 Staff Manager,
London Office, JFE Steel
(Former Products Service & Development Dept.,
Chita Works)

2.2 Material Design for High Toughness

In improving the low temperature toughness of steel pipes, it is necessary to enhance the performance of the steel coils used as starting materials. In particular, since seam welding of HFW pipes is accomplished by generation of resistance heat by a high frequency electrical current without using a welding wire, the weld is formed with the same composition as the base material. This means that the properties of the base material and weld of the pipe must be satisfied simultaneously by the composition design of the hot coil used as the starting material. Therefore, in material design, first, the effects of the chemical composition and microstructure on the toughness of the starting steel coils were evaluated.

In general, toughness tends to be deteriorated by increased contents of alloying elements. In particular, however, toughness decreases due to hardening of the weld when the carbon equivalent is high. Although the toughness of the base material is largely affected by the microstructure of the steel coil, coarse carbides precipitate easily at higher C contents. **Photo 1** shows an example of the influence of the microstructure of X70 grade HFW line pipe on toughness (85% SATT) in the DWTT. Because toughness is deteriorated by the formation of hard secondary phases such as coarse pearlite, martensite, etc., and these secondary phases have a negative effect on toughness by promoting propagation of cracks, it is particularly necessary to reduce these phases in both the base material and the weld. As mentioned above,

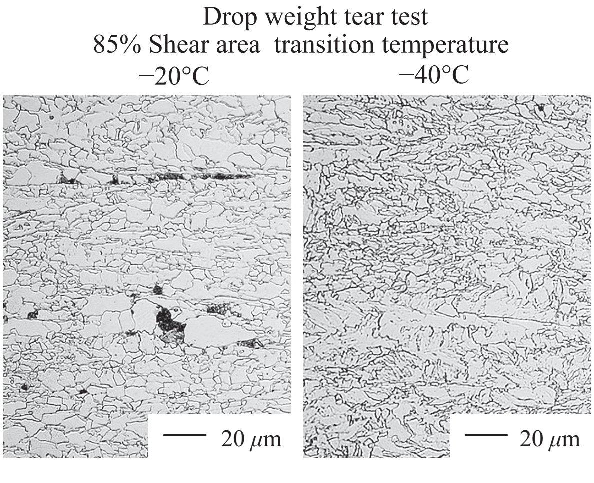


Photo 1 Influence of microstructure on toughness (API X70 electric resistance welded linepipe)

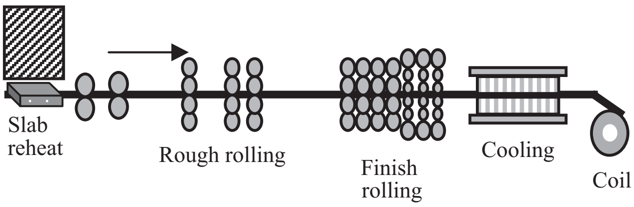


Fig. 1 Hot rolling process

HFW pipes are manufactured using hot coils as the starting material. In the manufacture of hot coils, the cooling stop temperature in the coiling process (**Fig. 1**) is frequently more than 500°C. Here, micro-alloy elements such as Nb, V, and Ti are added to secure precipitation strengthening by formation of carbonitrides in the steel. Active use of the precipitates of these micro-alloy elements is effective for improving the strength of steels with low carbon equivalents. JFE Steel studied the chemical composition and manufacturing conditions for strengthening by this approach, and adopted a design that secures strength mainly by controlling the coiling temperature in the hot rolling process to the temperature region where precipitation strengthening by microalloy elements can be utilized. However, simultaneously with this, precipitation of a coarse hard secondary phase, i.e., pearlite, and coarsening of ferrite tend to occur easily, and these phenomena deteriorate toughness. Therefore, the following design concepts were introduced.

(1) In order to suppress the formation of coarse hard phases, namely, pearlite and martensite, the C content is reduced to an appropriate level at which the strength of the X80 grade can be secured.
(2) Formation of coarse ferrite and pearlite during cooling is avoided by applying controlled cooling after finish rolling.

In other words, a single phase microstructure with no coarse hard phases is obtained by using steel with a reduced C content, with the aim of obtaining low carbon bainitic ferrite single phase steel coils in the hot coil manufacturing process. Reduction of the carbon equivalent is also necessary in order to obtain satisfactory weld toughness. Conversely, however, strength is reduced due to the decrease in hardenability when the carbon equivalent is reduced. Therefore, the aim was to satisfy both strength and toughness by optimizing the amount of added alloying elements that retard the ferrite transformation, such as Mn, Mo, and Ni, which are hardenability improving elements other than carbon, delaying and substantially preventing the pearlite transformation in the hot rolling process, and controlling cooling on the run-out table after finish rolling.

3. Study of Steel Composition

3.1 Experimental Method

Because the existence of hard secondary phases is considered to be a cause of reduced toughness in the base material and weld, a laboratory study was carried out by changing the C content while maintaining the strength of X80. The chemical compositions of the steels used in study of the effect of C content are shown in **Table 1**. Although the strength required in X80 can be obtained with carbon steel having a C content of 0.06%

Table 1 Chemical composition of the steel used

(mass%)

Steel	C	Si	Mn	P	S	Nb	Others	P_{cm}
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	0.01	0.002	0.05	V, Ti, Mo, Cu, Ni	0.15

P_{cm}=C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B

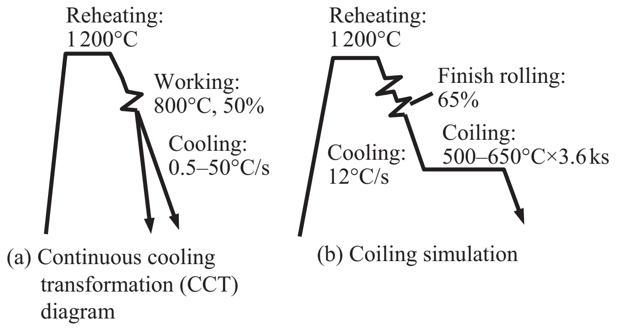


Fig. 2 Heat cycle

(Steel A), use in thin-walled materials and conventional, comparatively moderate environments is assumed. Steel B is a steel in which the C content was reduced to 0.04% based on the thinking described in this paper, and was designed considering applications that require low temperature toughness at −20°C and under. The continuous cooling transformation (CCT) diagram of this steel B was measured using the heat cycle shown in **Fig. 2**(a). Transformation was detected by the volume expansion associated with the austenite-ferrite transformation during cooling after hot working, and the cooling conditions for obtaining a fine single phase microstructure of bainitic ferrite were clarified by observation of the microstructure.

The effect of reduction of C contents was also evaluated by performing laboratory-scale hot rolling of Steels A and B, including the coiling process. The heat cycle in this experimental processing is shown in Fig. 2(b). The microstructures were observed after simulating the coiling process following hot rolling and cooling, and holding at 600°C.

3.2 Experimental Results

First, the measured results of the transformation behavior of Steel B by the CCT diagram are shown in **Fig. 3**. As can be seen in the microstructure obtained at the cooling rate of 10°C/s, bainitic ferrite formed when a high cooling rate was used, and the aimed single phase microstructure was obtained. The transformation start temperature in this case is around 600°C, and the critical cooling rate which was the lower limit for obtaining a single phase microstructure was approximately 10°C/s. The pearlite transformation starts at 600°C or higher incase cooling rate was lower than the critical cooling

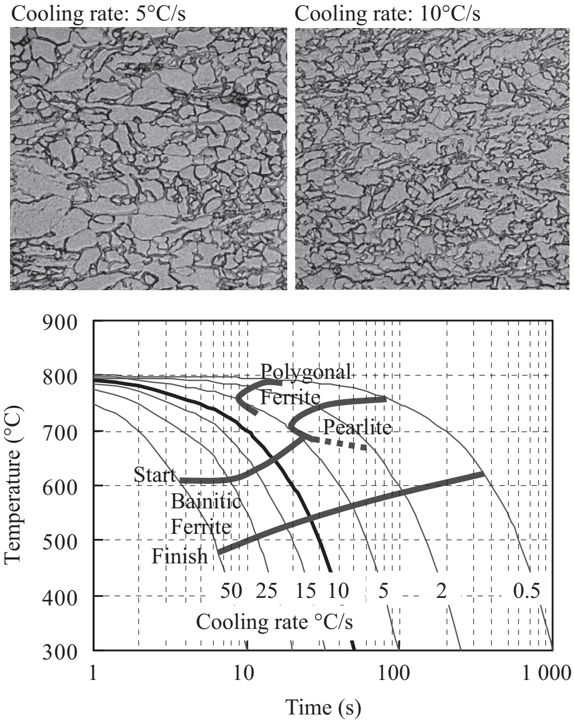


Fig. 3 Continuous cooling transformation diagram of steel B

rate. As an example of microstructures that was transformed at a comparatively high temperature, namely, polygonal ferrite and pearlite, Fig. 3 also shows the microstructure that formed at the cooling rate of 5°C/s. It is necessary to avoid the formation of this microstructure, as it is a coarse microstructure in comparison with bainitic ferrite and is a factor in reduced toughness. The critical cooling rate for formation of bainitic ferrite in Steel B is on a level at which control is sufficiently possible when manufacturing X80 grade hot coils. This experiment showed the possibility of obtaining the bainitic ferrite single phase microstructure by controlling the steel composition and cooling rate.

Next, hot rolling of Steel A and Steel B was performed in order to verify phase formation. The results are shown in **Photo 2**. After coiling at 600°C, pearlite and martensite had formed in Steel A which contains 0.06% C. In contrast, with Steel B, which has a reduced

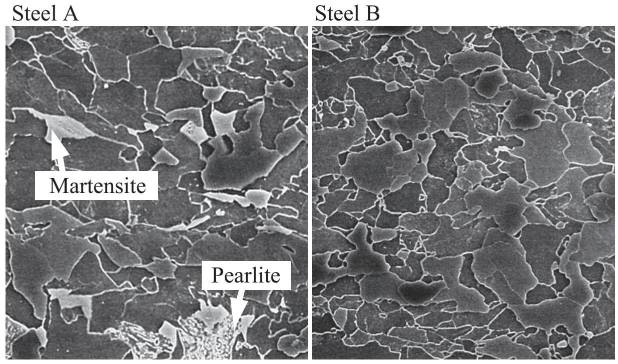


Photo 2 Effect of carbon on the microstructure

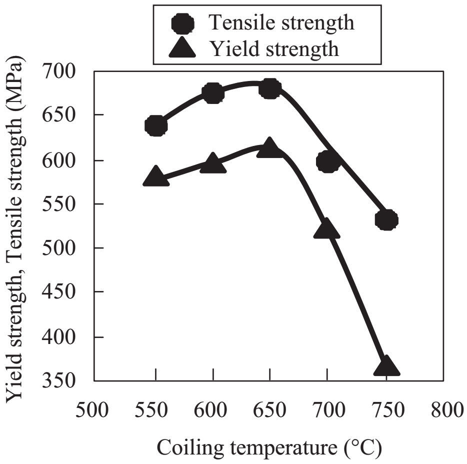


Fig. 4 Effect of coiling temperature on the strength

C content, a single phase microstructure of bainitic ferrite was obtained, and pearlite and martensite were not observed. Accordingly, this rolling experiment clarified the fact that a microstructure which does not contain coarse, hard secondary phases can be obtained by the hot rolling process through coiling by using Steel B with reduced carbon contents. **Figure 4** shows the effect of the coiling temperature condition on the strength of Steel B. When the coiling temperature was in the temperature region from 550°C to 650°C, strength satisfied YS ≧ 555 MPa (YS: Yield strength) and TS ≧ 625 MPa (TS: Tensile strength) of X80.

3.3 Evaluation of Precipitation Strengthening

Since it is essential to utilize precipitation strengthening in combination with control of the microstructure morphology, the amount of precipitated Nb was also evaluated. **Figure 5** shows the results of measurements of precipitated Nb by electrolytic extraction. At coiling temperatures from 600°C to 650°C, high values were observed for both strength and precipitated Nb. Based on this fact, it can be inferred that a large quantity of fine Nb carbonitrides precipitated in the steel. Based on the fact that the precipitation peak of Nb carbonitrides is normally around 600°C, it is thought that coarsening of crystal grains of ferrite and precipitates of Nb occurs at coiling temperatures over 700°C, and as a result, strength is greatly reduced. As a conceivable explanation for the large decrease in the quantity of Nb precipitates at 550°C, it is considered possible that precipitation in fact occurred, but the precipitates could not be detected by extraction analysis of precipitates due to their extremely small size. From the above, it is conjectured that a bainitic ferrite microstructure containing fine precipitates of Nb, which has excellent strength and low temperature toughness, can be obtained at least in the coiling temperature region from 550°C to 650°C.

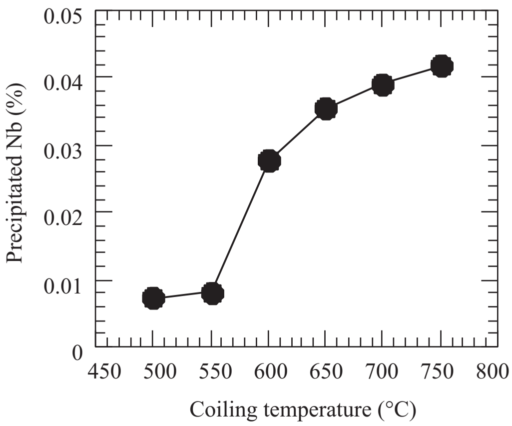


Fig. 5 Relation between precipitated Nb amount and coiling temperature (0.05% Nb steel)

4. Mechanical Properties of Developed Steel

4.1 Experimental Method

Based on the results of the study described above, X80 grade electric resistance welded steel pipes with wall thicknesses of 15.9–20.6 mm were manufactured using a composition system having a C content of 0.04%. The hot rolling conditions assumed production of hot coils with a reduction ratio of 65% or more in finish rolling using slabs with a thickness of 215 mm, and a coiling temperature of 450°C or higher. In pipemaking following hot rolling, pipes were welded by high frequency welding (HFW), and as post-annealing, quench temper (QT) treatment was performed by heating the weld seam to the Ac3 temperature or higher. Girth welding tests were also performed using the pipes after this pipemaking process.

4.2 Experimental Results

Figure 6 shows the results of the API tensile test of the pipe transverse direction. The arrows in this figure show the strength range of API X80. These results indicate that the strengths: YS, TS are matched the API standard over certain coiling temperatures. The weld seams also satisfied X80 class strength.

Figure 7 shows the results of the Charpy impact test. The Charpy absorbed energy of the base material (pipe body) was more than 300 J even at the test temperature of −60°C, and thus showed satisfactory results. The weld seam also displayed ductile fracture at −60°C, showing a high energy value. In particular, a high ductile area was obtained at low temperatures by optimizing the seam welding conditions and post-annealing conditions. The results for 85% SATT in the DWTT of the base material satisfied the target of −20°C.

Table 2 shows the girth welding test results. Welding heat input was practical level which does not hinder welding efficiency, and the strength of the weld metal was overmatched. In tensile test of the joint, fracture

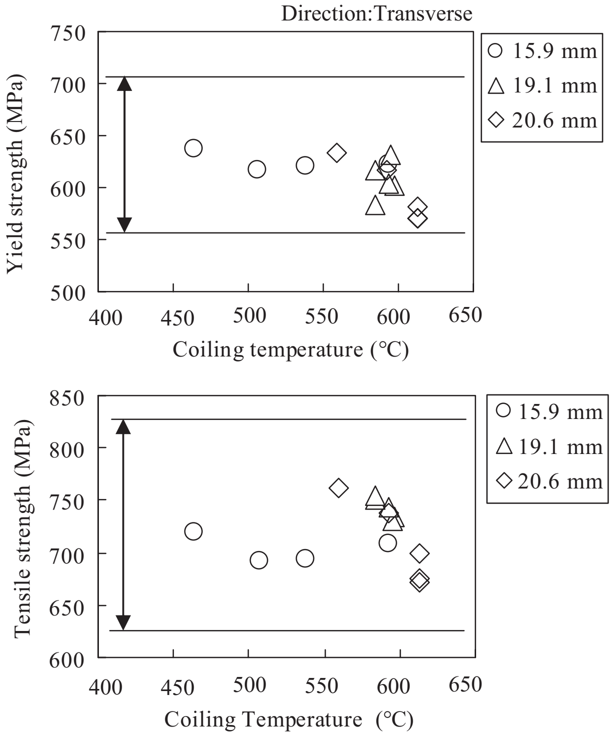


Fig. 6 Tensile properties of API X80 pipes

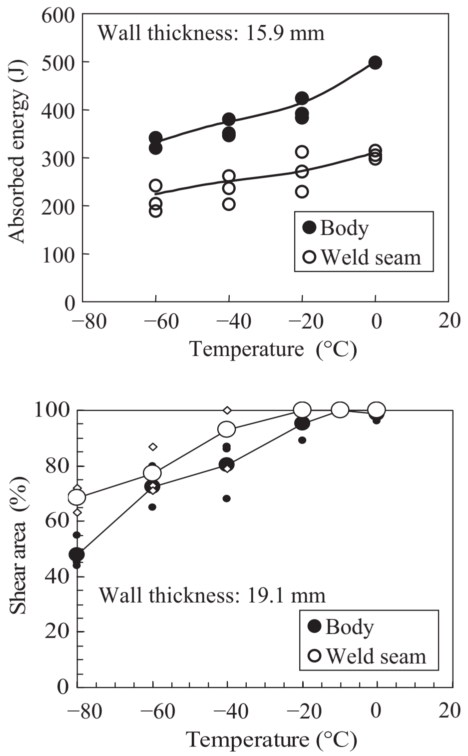
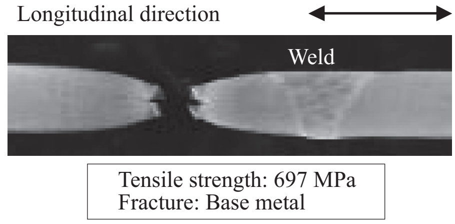


Fig. 7 Charpy V notch test results

Table 2 Girth welding test results

Welding procedure	Welding wire (Filler)	Strength of weld metal	Heat input (Average)
SMAW: 9 Passes	Low H 690 MPa	Overmatch	12 kJ/cm

Tensile test result



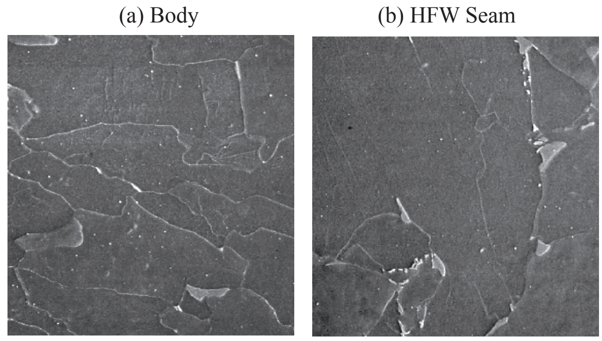


Photo 3 Microstructure of electric resistance welded pipe

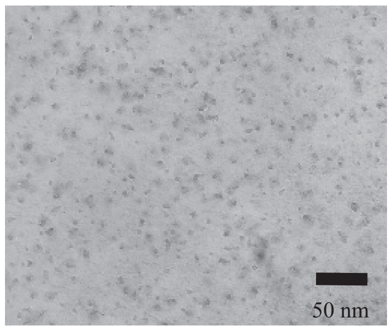


Photo 4 Transmission electron microscope micrograph of electric resistance welded pipe body

occurred in the base material in all cases, and the results satisfied the strength for X80 class. Satisfactory joint properties were also obtained in welding without pre-heating.

4.3 Evaluation of Microstructure and Discussion

Photo 3 shows the microstructures of the pipe body and HFW weld seam. The body is a single phase of bainitic ferrite which does not contain coarse pearlite and martensite. **Photo 4** shows the results of transmission electron microscope observation of the pipe body material. As a large quantity of Nb carbides is finely dispersed in the bainitic ferrite, it can be understood that precipitation strengthening contributes to securing strength. Furthermore, it is considered that the material displayed a high Charpy absorbed energy value because this is a homogeneous microstructure which is free of coarse pearlite and martensite.

Although a slight amount of a comparatively small secondary phase exists in the weld seam microstructure in Photo 3, the microstructure of the weld seam was substantially a single phase of bainitic ferrite. Based on the fact that this is a composition system in which C contents were reduced as far as possible, it is thought that this single phase composition was obtained because carbides were not dissolved as a result of the welding heat input, and coarse secondary phases such as pearlite were not precipitated by reprecipitation of solid solution of C. Moreover, low temperature toughness was obtained in the weld while maintaining a high strength level, and the mechanical property targets were amply satisfied, because basically the same bainitic ferrite single phase microstructure was retained after welding, and the material was free of coarse high temperature transformation phases such as polygonal ferrite, etc.

5. Conclusion

X80 line pipe with excellent low temperature toughness was commercialized using a hot coil-electric resistance welded pipe process. The hot coil used as the starting material was designed with the aim of obtaining a uniform bainitic ferrite single phase structure while preventing formation of coarse pearlite and martensite, which deteriorate toughness, and securing weld properties as a low carbon equivalent composition. In particular, studies of the effect of reduction of C contents and the hot rolling conditions were carried out in order to realize these aims. The following results were obtained.

(1) The hot rolling cooling conditions for obtaining a single phase microstructure in steel with the C content reduced to 0.04% were studied. As a result, it was found that a bainitic ferrite single phase microstructure with finely dispersed Nb precipitates can be obtained by performing cooling at or above the critical cooling rate and control of the coiling temperature.

(2) Electric resistance welded pipes with X80 grade strength and satisfactory base material toughness could be obtained by application of low C steel and controlled cooling in hot rolling.

(3) Satisfactory results were obtained for weld seam toughness, while also securing the strength of the seam joint, by optimizing the seam welding conditions and post-annealing conditions. The Charpy toughness of the seam displayed good values at -50°C and lower.

(4) Girth welding was possible without preheating, and satisfactory joint strength was also obtained, as fractures of the welded joints occurred in the pipe body (base material) in all cases.

Utilizing these excellent low temperature toughness properties, expanded application of X80 pipes is expected in diverse areas, including pipe line transportation of natural gas and oil field pipes such as conductors and risers.

References

1) Kawabata, F.; Amano, K.; Tanigawa, O.; Hatomura, T.; Sujita, Y. Proc of 11th Int. Conf. on Offshore Mechanics and Arctic Engineering. 1992, vol.V-B, p. 597–603.
2) Sugie, E.; Shiga, C.; Nakano, Y.; Amano, K.; Yoshimura, S.; Uesugi, T.; Kitagawa, M. 3rd Int. Conf. on Steel Rolling. ISIJ. 1985-09.
3) Okatsu, Mitsuhiro et al. CAMP-ISIJ. 1997, vol. 10, no. 6, p. 1431.
4) Okatsu, M.; Kawabata, F.; Amano, K. Proc. of the 16th Int. Conf. on OMAE. 1997, vol. 3, p. 119–124.