Abstract:
JFE Steel manufactures high performance steels used for energy development, transportation, and storage applications. In this paper, high performance UOE pipes for linepipe manufactured from steel plates are introduced. Keywords for development are high-strength, heavy wall thickness, high-deformability “HIPER™,” collapse-resistant for deep sea, sour resistance, and low-temperature toughness. At present JFE Steel is capable of providing high-end UOE pipes in numerous sizes and for a wide range of conditions.

1. Introduction
In recent years, new customer requirements have been applied to pipelines. In addition to severe service conditions, i.e., high pressure operation and use under low temperature environments/corrosive environments, strain-based design has been adopted more widely, assuming external forces accompanying construction of long-distance pipelines in seismic areas and the seabottom. As a result, in the pipe performance requirements demanded in pipelines, there is a heightened tendency toward addition of properties such as high strength, heavy wall thickness, low temperature toughness, high-strain capacity, and resistance to sour environments as composite specifications.

In response to this trend, JFE Steel has developed products which consider these new customer requirements through process development by strengthening its thermo-mechanical control process (TMCP) equipment for plates used as starting material for pipes, expanded application of online heat treatment process equipment (HOP™: Heat Treatment Online Process), and strengthening of the pipemaking plant, and has expanded its menu of UOE linepipe products which are capable of meeting composite specifications. Figure 1 shows available size range of API X80 pipes (API: The American Petroleum Institute).

This paper introduces high performance UOE pipe especially for linepipe products capable of satisfying composite specifications, including (1) concept of high-strain linepipes which can be used under strain-based design (SBD) and line of high-strength and strain linepipes, (2) ultra-heavy pipes for subsea use, (3) high...
strength X80 heavy wall pipes, (4) high strength X70 steel pipes for sour service, and particularly, (5) high strength X70 heavy wall pipe with high heat affect zone (HAZ) toughness, centering on the performance of these steel pipes.

2. High-Strain Linepipe HIPER™

2.1 Basic Concept of High-Strain Linepipes

HIPER™ is a high-strain linepipe which was developed to increase the safety of high strength pipelines to the same or a higher level than pipelines of conventional strength\(^1 \text{--}^3\). With HIPER™, it is possible to improve strain capacity without increasing pipe wall thickness\(^1 \text{--}^3\). Application of HIPER™ to natural gas pipelines makes it possible to improve pipeline integrity in seismic zones and discontinuous permafrost areas while minimizing increases in construction costs\(^1 \text{--}^3\). As features of high strain pipes, since the pipe weight, transportation costs, and welding time and construction period can all be reduced, corresponding to the amount by which the pipe thickness is not increased, this is an environment-friendly product with a large CO\(_2\) reduction effect.

Because an analytical solution predicting the critical local buckling strain under bending deformation is not required, a number of semi-empirical formulas have been proposed based on bending-buckling test data\(^4\). Figure 2 shows several critical local bending-buckling strain curves calculated using representative semi-empirical formulas. The range of application of these semi-empirical formulas is X65 grade line pipe and higher. Although the semi-empirical formulas do not display individual correspondence with the test data in Fig. 2, the formulas are defined so that each of the data falls within the envelop of the lower bound and can therefore be generalized by Eq. (1). However, because Eq. (1) does not consider strain-hardening properties, it can be understood that the wall thickness must be increased in order to improve the strain capacity of the linepipe.

\[
\varepsilon_{\text{crit-bend}} = A \left( \frac{t}{D} \right)^m
\]  \hspace{1cm} (1)

where, \(t\): wall thickness, \(D\): average pipe diameter. \(A\): constant, and \(m\): index, and are values which are obtained from test data.

In contrast to Eq. (1), semi-empirical formulas which consider strain-hardening properties will be introduced in the following. These are semi-empirical formulas that estimate the critical compressive local buckling strain and can express the strain capacity of linepipes as a function of the strain hardening parameter of the material\(^3\).

In round-house type stress-strain curves, if the relationship of stress and total strain is expressed by the power-law function, the critical local buckling strain of a pipe under axial compression can be expressed by Eq. (2).

\[
\varepsilon_{\text{crit}} = \frac{4}{3} \sqrt{n \frac{t}{D}}
\]  \hspace{1cm} (2)

where, \(\varepsilon_{\text{crit}}\): critical local buckling strain and \(n\): strain-hardening exponent.

If the stress-strain curve is expressed by the Ramberg-Osgood equation\(^5\) (R-O equation), the critical local buckling strain of a pipe under axial compression can be expressed by Eq. (3)\(^6\).

\[
\varepsilon_{\text{crit}} = \frac{\sigma_0}{E} \left( \frac{\sigma_0}{\sigma_y} \right)^3 + \frac{\sigma_0}{E} \left( \frac{\sigma_0}{\sigma_y} \right)^N
\]  \hspace{1cm} (3)

where, \(E\): Young’s modulus, \(\alpha\), \(\sigma_0\), \(N\): constants of the R-O equation, and \(\sigma_y\): critical compressive stress.

If the relationship between stress and plastic strain is expressed by the power-law function, the critical local buckling total strain of a pipe under axial compression can be expressed by Eq. (4), and the critical local buckling plastic strain can be expressed by Eq. (5)\(^7\).

\[
\varepsilon_{\text{crit}} = \frac{\sigma_0}{E} - \frac{\sigma_0}{2E} (1 + n) + \frac{4}{3} \sqrt{n \left( \frac{t}{D} \right)}
\]  \hspace{1cm} (4)

\[
\varepsilon_{\text{pcrit}} = \frac{4}{3} \sqrt{n \left( \frac{t}{D} \right)} - \frac{\sigma_0}{2E} (1 + n)
\]  \hspace{1cm} (5)

where, \(\varepsilon_{\text{crit}}\): critical local buckling total strain, \(\varepsilon_{\text{pcrit}}\): critical local buckling plastic strain, and \(E\): Young’s modulus, \(\sigma_0\): yield stress.

Eqs. (2)–(4) are analytical solutions which predict the critical local buckling strain of a steel pipe under
axial compressive deformation. Using these formulas, it is possible to obtain the strain-hardening properties which HIPER™ should satisfy for the strain demand in the structural design of pipelines. Although several additional steps are necessary to predict the critical local bending-buckling strain, Eqs. (2)–(4) are the basic formulas in the material design of high strain linepipe.

### 2.2 Properties of High Strain Linepipe

JFE Steel developed the high strain linepipe HIPER™ with excellent resistance to buckling by control of the dual-phase microstructure and optimization of the stress-strain curve, and has completed commercialization of grades from X52 to X100. Two types are used in control of the dual-phase microstructure, namely, the ferrite-bainite type, which is applied to grades X60-X65, and the bainite-MA type (MA: Martensite-austenite constituent), which is applied to high strength grades of X70 and higher. Typical microstructures of JFE Steel’s high strain linepipe are shown in Photo 1. X65 grade high strain linepipe has a ferrite-bainite structure, while high strain linepipe of X80 grade displays a finer bainite-MA microstructure$^{[3]}$.

The anti-corrosion polymer coating is applied to linepipes. As the aging effect of heating during coating treatment increases the yield strength of the material compared to the as-UOE condition, there are cases in which mechanical properties after coating are required in high strain linepipe. With steel for bainite-MA type high strain linepipe, previous studies clarified the fact that the content of solute carbon is reduced by fine precipitation of carbides during heating by HOP™, and dislocations in the bainite are reduced by tempering; as a result, strain aging hardening is slight, and there is little change in strain capacity after coating$^{[4]}$. Therefore, the bainite-MA microstructure is suitable for application to high strength pipelines of X70 and higher when coating treatment is applied.

The following presents an example of the production of high strain X80 linepipe. Table 1 is an example of the target values of tensile properties in longitudinal direction, which were decided through consultation with the pipeline designer. These properties were calculated by the method described in the previous section based on the strain capacity required in the region where the pipelines were to be installed. The yield ratio (YR) and stress ratio were specified, and uniform elongation was also specified. The stress ratio is the ratio of stress when strain is 1.5% and stress when strain is 0.5%. The circumferential tensile specifications conform to API 5L PSL2.

HIPER™ was applied in the plate manufacturing process with the aim of achieving a bainite-MA dual-phase microstructure with the MA fraction controlled to 5% or more in order to obtain the target stress ratio. Examples of the mechanical properties of the manufactured linepipes are shown in Table 2. As a coating simulation, the properties after heat treatment at $200°C \times 5$ min using a salt bath are also shown. Although the properties change slightly due to the aging treatment, both pipes

### Table 2 Examples of mechanical properties of API X80 (API: The American Petroleum Institute) high strain linepipes

<table>
<thead>
<tr>
<th>API Grade</th>
<th>Dimension OD (mm) WT (mm)</th>
<th>Condition</th>
<th>Longitudinal tensile properties</th>
<th>Charpy impact test, $E$ at $-10°C$ (J)</th>
<th>DWTT 2) SA at 0°C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X80</td>
<td>1219 22.0</td>
<td>As UOE 200°C Coated</td>
<td>YS (MPa) TS (MPa) YR* (%) $\sigma_{1.5%}\sigma_{0.5%}$ uEL* (%)</td>
<td>544 692 79 1.14 9.0</td>
<td>249 98</td>
</tr>
<tr>
<td></td>
<td>1219 26.4</td>
<td>As UOE 200°C Coated</td>
<td>560 689 81 1.12 9.2</td>
<td>241 100</td>
<td></td>
</tr>
</tbody>
</table>

* Customer specifications for high strain linepipe are added to API specifications. 
1) Rectangular specimen 
2) DWTT on 26.4 mm WT pipe was done by reduced t/9 mm specimen at $-11°C$.

OD: Outside diameter WT: Wall thickness YS: Yield strength TS: Tensile strength YR: Yield ratio $\sigma_{1.5%}/\sigma_{0.5%}$: Stress ratio uEL: Uniform elongation DWTT: Drop weight tear test $E$: Absorbed energy SA: Share area
Development of High Performance UOE Pipe for Linepipe

satisfy the specifications for high strain capacity. Furthermore, both Charpy toughness and drop weight tear test (DWTT) properties are satisfactory.

Histograms of the longitudinal uniform elongation and stress ratio of the manufactured pipes are shown in Figs. 3 and 4, respectively. As the target properties are amply satisfied in mass production, stable production of high strain linepipe has been realized.

3. Heavy Wall Linepipe for Deep Water Pipeline

Offshore gas pipeline development has been expanding toward deeper water region that requires pipes to have strong resistance against collapse by external pressure. The DNV standard, DNV-OS-F101 (DNV: Det Norske Veritas), is the major guideline for the design of offshore pipelines, which requires thicker wall to increase collapse resistance.

Other important material and structural parameters for controlling the collapse pressure of deepwater pipelines are compressive yield strength and roundness of the pipe. In the DNV standard, compressive yield strength is given by the tensile yield strength multiplied by the fabrication factor, $\alpha_{\text{fab}}$. Fabrication factor is specified as $\alpha_{\text{fab}} = 0.85$ for the linepipes manufactured by U-O-E process since the compressive yield strength is usually lower than tensile yield strength. Pre-straining of pipe body during cold forming of pipe, such as expansion process, considerably reduces yield strength in the compression test. This is because of the Bauschinger effect. Therefore, prevention of the Bauschinger effect is an important issue for enhancing compressive strength of pipes.

In addition to compressive strength, there are many other stringent material requirements for the linepipes used for deepwater pipelines. Advanced technologies in TMCP in plate manufacturing process made it possible to balance strength and toughness of heavy gauge linepipe as well as compressive strength. This chapter introduces a microstructure control for improving compressive strength while balancing other material properties. Production results of grade X65 linepipe with 36.6 mm wall thickness for offshore pipeline were also introduced.

3.1 Microstructural Factors Governing Compressive Strength of UOE Pipes

Circumferential compressive yield strength of UOE pipe is usually lower than that of tensile yield strength because of the Bauschinger effect due to the mechanical expansion applied as a final manufacturing process.

Therefore, a simple way to reduce the Bauschinger effect is to reduce the expansion rate. However, a certain level of expansion is necessary for improving roundness of the pipe. Pipe coating process, which requires heating of the pipe up to around 200°C, is also an effective way to increase compressive yield strength by strain aging $^{10}$. Nevertheless the most reliable measure to maximize the collapse resistance of pipe is to improve the material property itself without modifying the manufacturing process.

To further increase compressive strength, it is necessary to reduce the Bauschinger effect. Since the Bauschinger effect is caused by the back stress induced by dislocation localization, obstacles against dislocation movement can cause the Bauschinger effect. Hard second phases in steel, such as cementite or martensite, increases the back stress.

Bainitic microstructure design is widely used for high strength linepipe steels, which is produced by applying controlled rolling and accelerated cooling. However, low carbon bainite often involves MA constituent, which is formed during air cooling after accelerated cooling. This hard second phase is considered to enhance the Bauschinger effect same as martensite or cementite, and need to be removed for reducing the Bauschinger effect. One of the possible measures to remove MA is to apply HOP™ process.

In order to investigate the effect of MA on the Baus-
chinger effect, a cyclic loading test was conducted using grade X65 plates with conventional and HOP™ process (Fig. 5). The chemical compositions of the steel were 0.05C-0.3Si-1.3Mn-Ni-Mo-Nb, and the plate thickness was 33 mm. The microstructure of the steel plates in the quarter thick region is shown in Photo 2. In the steel with the conventional process, it is seen that MA constituents, marked by arrow in the picture, are formed in the bainite matrix. On the other hand, it is clear that almost no MA was seen in the steel with the HOP™ process.

Bauschinger effect factor is plotted vs. compressive prestrain for both conventional and HOP™ steels in Fig. 7. Bauschinger effect factor for HOP™ applied steel is always higher than that of conventional steel. Even with the small volume fraction of MA in the conventional steel, MA has significant influence on the Bauschinger effect. Therefore, reducing MA is an effective measure for preventing strength reduction by the Bauschinger effect.

3.2 Manufacturing Results of Heavy Wall Linepipes

Based on the above-mentioned study, mass-production of DNV-L450 grade heavy wall linepipes was carried out. The wall thickness was 36.6 mm, and the steel plates were manufactured by applying the online heating device HOP™.

Using these steel plates, linepipes with an outer diameter of 773.2 mm were manufactured by the UOE process. The chemical compositions of the base material steel plates is shown in Table 3. An uniform bainitic microstructure was confirmed, and virtually no MA was observed by microstructural observation. Table 4 shows the typical mechanical properties of the pipe. The pipe possesses strength and toughness satisfying DNV-L450 requirement, and compressive yield stress also shows a satisfactory value exceeding 90% of specified minimum yield strength (SMYS). The results of compressive strength and out-of-roundness of the pipe ends are shown in histograms in Figs. 8 and 9, respectively. With satisfactory higher compressive yield strength and excellent out-of-roundness as well as tensile strength and

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Others</th>
<th>Ceq</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNV-L450</td>
<td>0.04</td>
<td>0.3</td>
<td>1.3</td>
<td>0.01</td>
<td>0.01</td>
<td>Cr+Mo+Nb</td>
<td>0.35</td>
</tr>
</tbody>
</table>

DNV: Den Norske Veritas

Ceq = C + \frac{N\sigma}{5} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15}
Development of High Performance UOE Pipe for Linepipe

4.

X80 Heavy Wall Linepipes

Accompanying the trend toward long distance pipelines, linepipes with higher strength and heavier wall thickness are now demanded from the viewpoint of high pressure operation. In the 2nd West-East Gas Pipeline in China, API 5L grade X80 linepipes with the maximum wall thickness of 26.4 mm were used in order to transport natural gas at an operating pressure of 12 MPa\(^2\). In the design of pipelines for transportation of Alaskan natural gas to Canada and the United States, an ultra-high operating pressure of 17.5 MPa is being studied, and it is generally thought that heavy wall pipes of X80 will be necessary. With the trend toward heavier wall thickness products, simultaneously satisfying both strength and toughness generally becomes a difficult problem with steel materials, and the property requirements of these heavy wall thickness linepipes cannot be attained with the conventional chemical composition and manufacturing technique. Therefore, a new alloy design and plate manufacturing conditions different from the conventional method of material property control were studied, particularly for high strength linepipes with heavy wall thicknesses exceeding 30 mm. This chapter describes the study on the new alloy design and introduces grade X80 linepipes with a wall thickness of 38.1 mm which was manufactured based on the results.

4.1 Improvement of Strength and Toughness in Heavy Thickness Steel Plate

Plates for linepipes are manufactured using TMCP. In particular, accelerated cooling process is essential with high strength materials. In accelerated cooling of heavy plates, the cooling rate normally decreases as the plate thickness increases. JFE Steel developed the Super-OLAC\(^\text{TM}\), which realizes the theoretical limit of the cooling rate by water flow control technology, and also realized the same cooling rate in heavy gauge steel plates as with thin plates produced by conventional equipment. Nevertheless, there are limits to the increase in cooling capacity when producing heavy gauge steel plates exceeding 30 mm in thickness.

Therefore, in the design of the chemical composition of plates for linepipes, addition of boron (B) was studied to improve the strength and toughness of steel plate with heavy thickness. Figure 10 shows the results of plate rolling experiments using ingots in laboratory vacuum furnace when the amounts of various added alloying elements were changed, and with and without B addition.

Table 4 Typical mechanical properties of heavy wall DNV-L450 linepipe (DNV: Det Norske Veritas)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Dimension</th>
<th>Tensile properties(^1)</th>
<th>Compressive yield strength(^2) (MPa)</th>
<th>Charpy impact test (\varepsilon (J)) at (-13^\circ)C</th>
<th>DWTT test(^3) SA at (-20^\circ)C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNV-L450</td>
<td>OD, D (mm) WT, t (mm) D/t</td>
<td>YS (MPa) TS (MPa) El (%)</td>
<td>Body 180° BM WM FL</td>
<td>447 443 267 279</td>
<td></td>
</tr>
<tr>
<td></td>
<td>773.2 36.6 21.1 482 557 32</td>
<td></td>
<td></td>
<td>98</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)Round bar specimen (Φ12.5 mm) Trans. dorection
\(^2\)ASTM E9 (Φ20 mm×L60 mm) specimen (ASTM: The American Society for Testing and Materials)
\(^3\)t19 mm Reduced thickness specimen


Fig. 8 Compression test record of heavy wall thickness linepipes

Fig. 9 Record of out-of-roundness of heavy wall thickness linepipes
Development of High Performance UOE Pipe for Linepipe

The slabs were heated at 1,150°C and rolled. Plate rolling was finished at 780°C, followed by accelerated cooling, and finally, heating simulating the HOP\textsuperscript{TM} process was applied to the rolled plate\textsuperscript{13).} With both the B-added and B-free steel, the tensile strength of the plates increased as the weld crack parameter $P_{CM}$ increased. However, at the same $P_{CM}$, higher tensile strength was obtained with the B-added steel. In other words, when the B-added composition design is used, it is possible to adopt a lower $P_{CM}$ with the same strength grade. Therefore, it is not necessary to increase the pre-heating temperature for prevention of weld cold cracking calculated from the $P_{CM}$ value, and excellent field weldability can also be realized.

**Figure 11** shows the continuous cooling transformation diagrams (CCT diagrams) of the two types of steel, i.e., B-added and B-free, when the $P_{CM}$ value was set at 0.21. It can be understood that the ferrite transformation in the low cooling rate range, which can be seen in the B-free steel, is suppressed by B addition, and the bainite transformation start temperature (Bs point) and finish temperature (Bf) also shift to lower temperatures. This shift to lower bainite transformation temperatures is considered to be the main factor in the increased strength of the B-added steel when ACC is applied.

**Figure 12** shows the relationship between the tensile strength and the Charpy fracture appearance transition temperature ($v_{Trs}$) of steel plates in a rolling experiment using B-added and B-free steels. Under the same rolling conditions, no change can be recognized in the strength-toughness balance, irrespective of whether B is added or not. On the other hand, at the same strength, $v_{Trs}$ improves to the low temperature side with the B-added steels when the rolling finishing temperature is decreased.

**Photo 3** shows the results of observation of the microstructures of rolled plates in the cases of high and low rolling finishing temperatures. In both cases, the bainite structure formed by transformation during accelerated cooling is the main phase, and dispersed MA formed in subsequently heating by HOP\textsuperscript{TM} is observed.

**4.2 Manufacturing Results of Extra-Heavy Wall X80 Linepipes**

Based on the above-mentioned study results, the
Development of High Performance UOE Pipe for Linepipe

The chemical composition design of the heavy thickness steel plate and the plate manufacturing conditions were optimized, and grade X80 linepipes with a wall thickness of 38.1 mm were manufactured on a trial basis. The chemical composition of the steel for the pipe is shown in Table 5. The content of B was 0.007 mass%, and the $P_{CM}$ value was adjusted to 0.21 by addition of Cu, Ni, Mo, and other alloy elements. Slabs were manufactured by continuous casting and rolled to plates with a thickness of 38.1 mm by the plate rolling-Super-OLAC™ process, and formed into pipes with an outer diameter of 1 216 mm by the new pipemaking equipment. The microstructure of the pipe body material is shown in Photo 4. The microstructure with fine dispersed MA in bainite was obtained at both the 1/4 thickness and 1/2 thickness positions, and both the strength and toughness of X80 grade requirement were achieved by the Super-OLAC™ process after the low rolling finishing temperature. Table 6 shows the mechanical properties of the pipe. The API 5L X80 standard yield strength (YS) and tensile strength (TS) were satisfied in both circumferential direction and longitudinal direction, and the pipe showed excellent deformability, i.e., L-direction YR $\leq$ 85% and uniform elongation $\geq$ 5%. In addition, the Charpy toughness and DWTT toughness showed satisfactory values at $-20^\circ$C.

### 5. Grade X70 Linepipe for Sour Service

Linepipes used in the pipeline transporting sour gas containing H$_2$S need to have strong resistance to hydrogen induced cracking (HIC). In order to prevent HIC, it is necessary to (1) reduce inclusions which act as crack initiation sites, (2) reduce center segregation which increases hardness and enhances crack propagation. For these reasons the steel need to have higher level of cleanliness with low P and S content and addition of alloying elements such as C, Mn, and other elements are strictly controlled.

On the other hand, for the purpose of cost reduction of pipeline construction and operation, higher grade linepipes for sour service are expected. To achieve higher strength over grade X65 steels need to have richer chemistries, but this invites the formation of hard second phase such as MA which in turn increases susceptibility to HIC.

This chapter introduces the development of a new TMCP technology for achieving high strength exceeding X65 with a homogeneous microstructure without hard MA phase and trial production result of grade X70 UOE linepipe for heavy sour application by applying the state of the art technology.

#### 5.1 Microstructure Control for Improved HIC Resistance

In order to produce such a high strength and high performance linepipe steels, JFE Steel developed the online heat treatment process HOP™. Combination with Super-OLAC™ and HOP™ has enabled novel metallurgical controlling that cannot be achieved by the conventional TMCP process. Material design concepts for sour resistant linepipe steel are: (1) transformation strengthening by homogeneous and fine bainitic microstructure obtained through higher cooling rate with Super-OLAC™ by accelerated cooling, (2) promoting precipitation of alloy carbides by rapid heating immediately after accelerated cooling, and (3) preventing MA precipitation of alloy carbides by rapid heating immediately after accelerated cooling.
Development of High Performance UOE Pipe for Linepipe

Using a 0.05C-1.25Mn-0.1Mo-0.04Nb-0.045V-Ti steel, verification was performed by conducting a laboratory experiment under the TMCP conditions shown in Fig. 13. Laboratory rolling was performed at two levels, one under the conventional accelerated controlled cooling conditions (as-accelerated controlled cooling (ACC) material), and the other, under the above-mentioned conditions applying the HOP™.

Photo 5 shows the microstructures of the respective laboratory rolled materials. In the as-ACC steel, the results of scanning electron microscope observation after 2-stage electrical etching confirmed the existence of MA, which is visible as a white grain-like form in the bainite matrix. In contrast, virtually no MA was observed in the HOP™ steel. Figure 14 shows the results of a tensile test of the laboratory-rolled steel. In comparison with the as-ACC steel, the HOP™ steel shows about 80 MPa higher YS and approximately 50 MPa higher TS.

Experimental results demonstrated that prevention of MA formation and precipitation strengthening can be achieved by the new TMCP process using HOP™, which can be applied to higher grade linepipe steel for sour service.

5.2 Manufacturing Results of Grade X70 Linepipe for Sour Service

Based on the results described above, API 5L grade X70 linepipes with sour resistance were manufactured using steel plates by applying the technology for uniform microstructure control in the plate thickness direction to reduce susceptibility to HIC. The pipe wall thickness was 19.1 mm. Plates were manufactured using the online heating device HOP™, and linepipes with an outer diameter of 914.4 mm were manufactured by the UOE process.

The chemical composition of the steel plates is shown in Table 7. The contents of C, P, and Mn were
the same as the conventional X65 steel for sour service, and a lower alloying design than the conventional non-sour X70 linepipe was adopted, namely, a $P_{CM}$ value of 0.14. Microstructure observation confirmed that the base material had a homogeneous bainitic microstructure without MA. Figure 16 shows the hardness distribution in the width direction of the plate. From the edge to the center, hardness differences were extremely small, as the Vickers hardness at the plate surface and 1/4 thickness position was 180–200 points. This demonstrates the homogeneous material properties throughout the plates. Table 8 shows examples of the mechanical properties of the pipe. The developed linepipe has enough strength which satisfies the API 5L X70 standard, and satisfactory properties were also obtained in the Charpy impact test and the DWTT test. For the HIC property, a 96-hours immersion experiment was performed under a condition of 100% H$_2$S gas saturation of solution A as specified in NACE TM0284 (NACE: The National Association of Corrosion Engineers). The results showed excellent HIC resistance, in which no cracking was found in all cases.

6. Heavy Wall Thickness X70 UOE Linepipe for Low Temperature Service

6.1 Issues of Seam Welding of Heavy Wall Thickness UOE Pipes

Accompanying high pressure operation of pipelines and use in deep waters, pipes with high strength and heavy wall thickness are being adopted. Under these conditions, pipes having high HAZ toughness are required, even in X70 heavy wall thickness pipes. Therefore, it is necessary to obtain both of high strength by means of addition of alloying elements and high HAZ toughness in the as-welded condition in thick wall double-side submerged arc welded pipes (DSAW).
Figure 17 shows the relationship between the heat input in welding of steel pipes with a wall thickness of 33 mm and the weld cooling rate (800–500°C). Under the conventional submerged arc welding (SAW) conditions, the average heat input of the inside and outside welds is 8.8 kJ/mm, and the weld cooling rate is slow, at approximately 4.0°C/s.

Reduction of the cooling rate accompanying increased welding heat input has negative effects on HAZ toughness, as it expands the toughness deterioration region comprising the coarse grain heat affected zone (CGHAZ) and intercritically reheated coarse grain heat affected zone (ICCGHAZ), and also causes coarsening of the prior austenite (γ) grain size. Figure 18 shows the effect of welding heat input on HAZ toughness of X70 welded joint (Thickness: 33.0 mm). As heat input decreases, vTrs decreases, and HAZ toughness improves.

6.2 Low Heat Input SAW Technology
Applying Smaller Diameter Welding Wire

As a technique for reducing heat input, a low heat input SAW technology using a smaller diameter welding wire as the leading electrode was developed, improving HAZ toughness in seam welds of heavy wall thickness X70.

The following may be mentioned as effects of using the smaller diameter welding wire as the leading electrode: (1) a high deposition rate can be obtained as a result of the increase in Joule heating accompanying the increased electrical resistance of the smaller diameter wire, and (2) arc energy density is increased by the higher current density, and simultaneously with this, the arc is focused by the electromagnetic pinch force and a deeper weld penetration depth can be obtained.

Figure 19 shows the effect of the wire diameter on the wire deposition rate with wires having diameters of 1.6 mm to 4.0 mm. In seam welding of UOE pipes, wires with diameter of 4.0 mm or 4.8 mm are generally used. However, the wire deposition rate is greatly increased by using a smaller diameter welding wire, and the effect of the smaller diameter wire is remarkable on the large current region.

Figure 20 shows the effect of the wire diameter on the penetration depth with wires of 1.6 mm to 4.0 mm. Penetration increases when smaller diameter wires are used, and the deepest penetration is obtained with a wire diameter of 2.4 mm or smaller.

Based on the results described above, a 2.4 mm in diameter wire was adopted as the leading electrode because it is possible to use of the large current with this welding technology and this size has a large effect in increasing the penetration depth and wire deposition rate. This small-diameter wire SAW technology enables welding with a smaller heat input than the conventional SAW technology. Moreover, the effect of heat input reduction becomes larger as the wall thickness increases.

To clarify the effect of this small-diameter wire SAW technology in improving HAZ toughness, welded joints of X70 (33.0 mm) were prepared experimentally using the small-diameter wire SAW technology, and the properties of the welds were evaluated. Table 9 shows the welding conditions. In comparison with the conventional method, the welding heat input was reduced by approximately 30% as the total of the inside and outside welds.

The cooling rate of the weld metal with the conventional method was approximately 4°C/s, but in contrast, that increases to approximately 10°C with small-diameter wire SAW. Photo 6 shows the CGHAZ microstructure around the fusion line at a depth of 7 mm below the surface layer of the outside weld metal. Accompanying the reduction of heat input, the prior γ grain size of the CGHAZ is refined. Table 10 shows the results of a HAZ Charpy test of the outside weld fusion line and the root fusion line (intersection of the inside...
Development of High Performance UOE Pipe for Linepipe

6.3 Manufacturing Results of Heavy Wall Thickness X70 UOE Linepipe

Heavy wall thickness X70 UOE pipes (30.9 mm) for low temperature service were manufactured on a trial basis applying the small-diameter wire SAW technology to seam welding. The welding conditions, a macrograph of the weld cross section, and the results of mechanical property tests are shown in Table 11, Photo 7, and Table 12, respectively. Sound welds with satisfactory lap of the inside weld bead and outside weld bead were obtained by application of the small-diameter wire SAW technology, and it was possible to manufacture pipes having excellent HAZ toughness of $\varepsilon_{-30^\circ C} \geq 100$ J in the Charpy tests of the inside weld, outside weld, and root fusion lines.
7. Conclusion

This paper introduced products developed by JFE Steel in response to new customer requirements for steel pipes for linepipes in recent years, using JFE Steel’s TMCP technology for steel plates used as materials for those pipes and steel pipe manufacturing technologies. Focusing on the keywords of high strength, heavy wall thickness, low temperature toughness, high deformability, and sour resistance, the lineup of products which is capable of meeting composite specifications for those properties was described.

In the future, JFE Steel will continue to develop steel plates and steel pipes for linepipes in response to increasingly advanced and diverse requirements by concentrating its steelmaking, plate manufacturing, and UOE pipemaking technologies, taking advantage of its distinctive features as an integrated steel maker, and will contribute to the development of the energy industries which the world demands by supplying outstanding steel products which are also environment-friendly.

References