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# Development of a High-Deformability Linepipe with Resistance to Strain-aged Hardening by HOP® (Heat-treatment On-line Process)[†]

OKATSU Mitsuhiro[*1] SHIKANAI Nobuo[*2] KONDO Joe[*3]

***Abstract:***

*When linepipes are installed in permafrost ground or seismic regions, where ground movement is likely to impose larger strain, they must have deformability sufficient to prevent local buckling and girth weld fractures. The pipes also require an external coating for corrosion resistance. During coatings, however, the heat imposed to the pipes can cause strain-aged hardening, which in terns increases the yield strength and yield ratio (Y/T). Thus, there is a strong demand for a high-strength, high-deformability linepipe with resistance to strain-aged hardening for high-strain applications. 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 bainite and martensite-austenite constituent (MA) microstructure can be obtained by applying HOP® (Heat-treatment On-line Process) subsequently after an accelerated cooling process. As an added advantage, this HOP also improves resistance to strain-aged hardening. The diffusible free C atoms in the steel can be reduced by carbide precipitation. A coating simulation test result for high deformability linepipe treated by HOP revealed excellent deformability after coating heating.*

## 1. Introduction

Recent studies have demonstrated the significant economical advantages of using higher-strength linepipes for long-distance pipelines. The chief advantages are reduced material costs and the improvement in the transportation efficiency brought about by the increased internal pressure. The pipelines now being constructed are often run through severe environment, such as cold regions, seismic regions, and deepwater and sour gas environments. These pipelines require properties, such as high toughness, high deformability, and sour resistance property in addition to high strength. One of the most challenging fields for pipeline development is development for seismic and permafrost regions. The ground movement in these regions is prone to induce large plastic deformation. Pipelines engineers have recently developed a new pipeline design methodology seismic and permafrost regions[1)]. The methodology is modeled after the new concept that pipelines require higher resistance against larger compressive and tensile strains. Linepipes need sufficient resistance to buckling, the critical failure event that results from compressive deformation. **Figure 1** shows how the maximum buckling strain and pipe diameter ($D$) related to the thickness ($t$) ratio for conventional pipes[2)]. The buckling behavior generally depends strongly on the pipe dimensions. The buckling strain decreases with increases in the $D/t$ ratio, that is, the ratio of pipe diameter to pipe thickness, and a thicker pipe needs to be used in fields with for large ground movement. A higher strength material also generally has lower uniform elongation, which means lower deformability. Higher strength-linepipes could take advantage of these opposing trends, and the thinner walls of the pipes would confer the benefit of reduced material costs. Suppliers thus need to develop a higher-

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[*2] Dr. Eng.,
General Manager, Plate & Shapes Res. Dept.,
Steel Res. Lab.,
JFE Steel

[*1] Senior Researcher Staff Manager,
Plate & Shapes Res. Dept.,
Steel Res. Lab.,
JFE Steel

[*3] Manager, Welded Pipe Sec.,
Products Design & Quality Control
for Steel Products Dept.,
West Japan Works,
JFE Steel

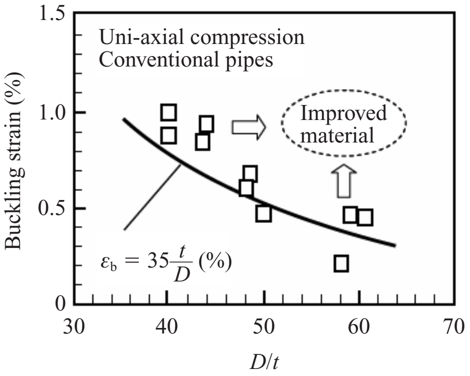


Fig. 1 Relationship between buckling strain by axial compression and pipe diameter to thickness ratio ($D/t$)

strength linepipe with higher deformability (that is, higher resistance to buckling), in order to take advantage of the improved properties for use in seismic and permafrost regions.

The deformability of steel pipes is improved by increasing the strain hardenability of the steel. Pipes with higher works hardening exponent ($n$-values) and round-house type stress-strain curves are reported to have a higher buckling strain[2)]. Strain hardenability is strongly affected by the microstructure of the steel. Steels with higher strain hardenability can be obtained with a dual-phase microstructure, consisting of a softer phase and harder phase. According to an analytical study conducted to clarify the optimum microstructural morphology[3,4)], the $n$-value increases as the strength difference between the matrix phase and second phase increases. This means that steels with a harder second phase have higher deformability.

Another important requirement is to prevent corrosion damage, a possible cause of gas leakage and fatal accidents. The general method to protect pipes from corrosion damages, is to apply a thicker external coating, such as a fusion bond epoxy (FBE) coating. During the coating process, the pipes are heated up to the temperature range in which the coating materials melt. A recent study indicated that the strain aging of the pipe incurred during coating heating could increase the yield strength of the pipe to some degree[5)]. This, in tern, increases the yield ratio ($Y/T$) and possibly worsens the deformability of the pipes. Thus another important requirement is to maintain the deformability of the pipe after coating heating.

JFE Steel developed a high-deformability linepipe with resistance to strain-aged hardening. The microstructure of the steel consisted of bainite matrix and martensite-austenite constituent (MA) as a second phase. This linepipe steel is manufactured by applying accelerated cooling followed by HOP® (Heat-treatment On-line Process). In this paper we introduce the metallurgical concept of the HOP treated high-deformability linepipe, and discuss the mechanism of resistance to strain-aged hardening. X70 to X100 high-deformability linepipes were manufactured by applying the HOP process on a trial production basis. The microstructural characteristics and mechanical properties of the newly developed linepipes are also introduced in this paper.

## 2. Dual-Phase Microstructural Control by HOP (Heat-treatment On-line Process) and Mechanical Properties of Bainite-MA Steel

### 2.1 Test Procedures

A dual-phase microstructure containing a harder second phase is well known to have a higher $n$-value[3,4)]. One way to achieve higher deformability is to use MA as a second phase. When doing so, the MA must have a volume fraction of certain level in order to obtain the higher deformability required. MA is a common phase observed in high-strength structural steel. Many of the high-grade linepipe steels recently manufactured by the thermo-mechanical control process (TMCP) process are characterized by a bainitic microstructure with MA formed inside the bainite phase. A higher carbon content of the steel increases the volume fraction of MA, but it degrades the weldability and toughness. This makes it challenging to achieve the MA phase in the required amount with the conventional TMCP process.

The effect of heat treatment after accelerated cooling was investigated in order to obtain a dual phase microstructure containing MA. **Table 1** shows the chemical compositions of the steels used for the test to investigate MA formation. The initial material was a 0.06 mass% carbon steels with added niobium. A series of 15.6 mm-thick steel plates were produced by applying two different processes. **Figure 2** shows schematic temperature profiles in plate manufacturing. In the conventional

Table 1 Chemical compositions of the steel used

(mass%)

| C | Si | Mn | P | S | Nb | Others |
|---|---|---|---|---|---|---|
| 0.06 | 0.2 | 1.8 | 0.01 | 0.001 | 0.04 | Cu, Ni, Mo, Ti |

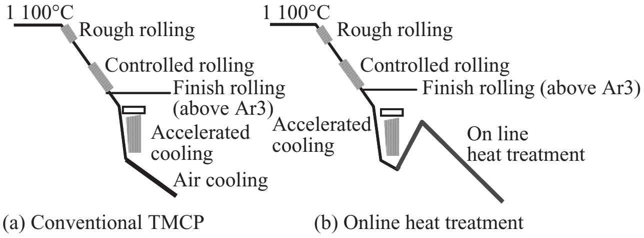


Fig. 2 Schematic illustration of TMCP conditions in plate production test

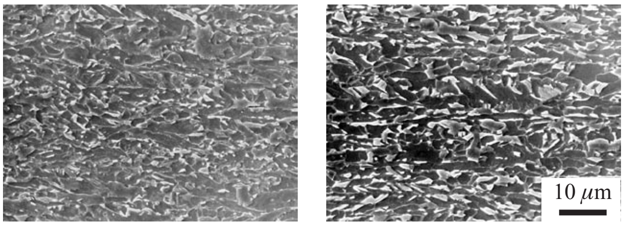
TMCP process, total rolling-reduction at the controlled rolling was 75%. After the controlled rolling, the accelerated cooling was commenced at a temperature above the Ar3 temperature, and the plate was then cooled in the air. In HOP, the plate was heated by an induction-heating device subsequently after the accelerated cooling. The controlled rolling and accelerated cooling conditions were the same in the HOP and conventional TMCP process. In both cases, the accelerated cooling was finished at the temperature below the starting temperature for bainite transformation and above the bainite transformation finishing temperature. An induction-heating device with a high heating capacity (sufficient to heat thick steel plate of up to 40 mm) was arranged on the plate production line behind the accelerated cooling device[6)] to heat the plate rapidly to appropriate temperature.

Microstructural observation was conducted on the plates in the longitudinal section. After polishing, the samples were etched by a two-stage electrical method. The MA appears as white portions after the etching was completed. The microstructure of the steels was observed by scanning electron microscopy (SEM).

These plates were then used to manufacture grade X80 UOE linepipes with a 32 inch (813 mm) diameter. The tensile properties of the linepipe were investigated by carrying out a tensile test in the longitudinal direction using a full-thickness specimen according to the API 5L standard. The *n*-value was calculated between 0.5% and 1.5% of strain in the stress-strain curve.

### 2.2 Test Results

**Photo 1** shows the SEM microphotographs of the plates produced by the conventional TMCP and HOP. The microstructure of the conventional TMCP steel consists of bainite, with a small amount of MA also observables. The HOP treated Steel, meanwhile, exhibited a large number of MA. The volume fraction of MA was about 7%. **Table 2** shows the tensile properties of both pipes. Both pipes had sufficient tensile strength for grade X80. The *Y*/*T* ratio of the conventional TMCP pipe, on the other hand, was higher than that of HOP treated pipe. HOP treated pipe had a sufficient volume fraction of MA, and a higher uniform elongation and *n*-value than the TMCP pipe.



(a) Conventional TMCP (b) HOP process

Photo 1 SEM microphotographs of the steels

### 2.3 Mechanism of MA Formation via HOP (Heat-treatment On-line Process)

**Figure 3** shows a schematic illustration of the changes in the microstructure during the HOP. The whole process consists of three stages: accelerated cooling (ACC), heat treatment by HOP, and cooling in the air. The ACC stops at above the temperature at which the bainite transformation finishes, where untransformed austenite remains. The microstructure at this stage consists of bainite and untransformed austenite. The heat treatment by HOP is applied immediately after the ACC. During the heating, carbon in bainite diffuses

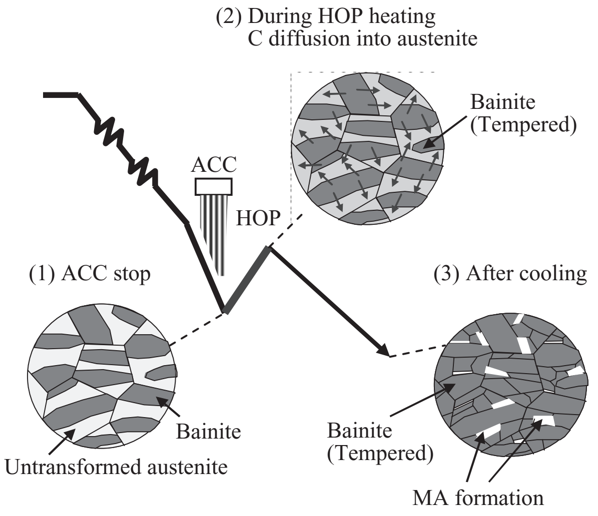


Fig. 3 Schematic illustration of microstructure change in the HOP process for dual phase control

Table 2 Longitudinal tensile properties of the pipes by conventional TMCP and HOP process

| Process | Dimensions | | | Longitudinal tensile properties | | | | |
|---|---|---|---|---|---|---|---|---|
| | OD (mm) | WT (mm) | *D*/*t* | YS (MPa) | TS (MPa) | *Y*/*T* (%) | uEl* (%) | *n*-value |
| Conventional TMCP | 813 | 15.6 | 52 | 564 | 657 | 86 | 9.8 | 0.09 |
| HOP process | 813 | 15.6 | 52 | 548 | 684 | 80 | 12.2 | 0.12 |

OD: Outer diameter YS: Yield strength
WT: Wall thickness TS: Tensile strength
*D*/*t*: OD/WT *Y*/*T*: YS/TS × 100
* uEl: uniform elongation

into austenite. The austenite with higher carbon content is retained after the heating, and the highly concentrate carbon in the austenite permits the transformation of this austenite into MA by air-cooling.

### 2.4 Effect of MA on Tensile and Impact Properties

The chemical composition of the steel and the accelerated cooling and heating conditions affect the volume fraction of MA. In the next part of study, the effect of volume fraction of the MA on the tensile and impact properties was investigated in laboratory. Laboratory slabs with the chemistries of 0.05C-0.2Si-1.5–1.8Mn-0–0.2Mo-0.04Nb-0.05V were used for changing the MA volume fraction. Plate rolling and HOP process were simulated using laboratory equipment. This resulted in the production of steel plates with a bainite-MA microstructure, with a change in the MA volume fraction changed from 0% to 7%.

**Figure 4** shows the effect of the volume fraction of MA on the *Y*/*T* ratio of the steel plate. The *Y*/*T* ratio fell as the MA volume fraction rose, and a *Y*/*T* ratio below 80% could be achieved by an MA volume fraction above 5%.

**Figure 5** shows the relation between the temperatures at which fractures appeared in the Charpy test (vTrs) and the tensile strengths of steels with different MA volume fractions. Steels with high and low MA volume fractions generally have the same toughness-strength balance. MA is a hard and brittle phase, and at times it can initiate brittle fracture. It is generally thought to be harmful for material toughness, with a particularly strong effect in reducing the heat affected zone (HAZ) toughness. Yet the morphology of MA formed in the HOP differs from that observable in the HAZ. As Photo 1 shows, the morphology of the MA phase formed in the HOP is rather granular, while the MA phase observed in HAZ region usually has a slender shape. Thus, the MA phase with the granular shape does not initiate brittle fracture, and the bainite-MA steels exhibited no deterioration of vTrs.

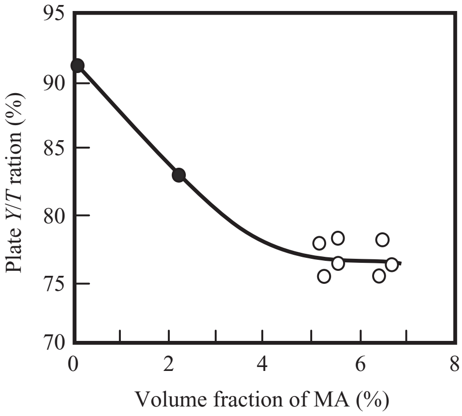


Fig. 4 Effect of volume fraction of MA on plate *Y*/*T* ratio

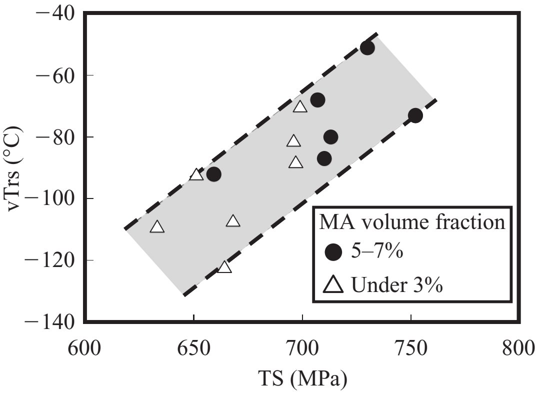


Fig. 5 Relationship between transition temperature on Charpy test and tensile strength

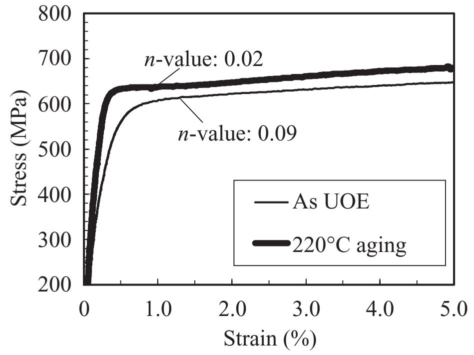
## 3. Strain Aging Behavior of the Steel with Bainite and MA Microstructure

### 3.1 Strain Aging by Coating Heating

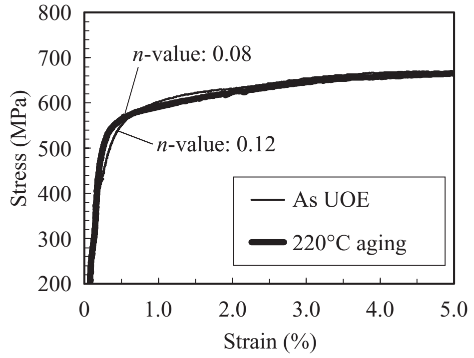
Strain aging is caused by the interaction of dislocations and diffusible carbon atoms. The dislocations induced by the processes of plate production and pipe formation are fixed by carbon atoms activated by heating, and this, in tern, increases the yield strength. The yield strength and *Y*/*T* ratio of the UOE pipe are reportedly increased by thermal coating5), and higher-strength linepipes produced by accelerated cooling with a lower cooling-stop temperature are reported to be more sensitive to strain aging7). Dislocations are thought to be induced by the phase transformation during the accelerated cooling, and diffusible carbon atoms may remain after accelerated cooling of the plate. This, in fact, may be one of the reasons for the strain aging induced pipe coating.

### 3.2 Coating Simulation Test

Laboratory coating simulation test was conducted in order to evaluate the strain aged hardening property of pipes both made from HOP treated steel and conventional TMCP steel, as shown in Table 2. Coupons for tensile specimens were taken from the both pipes in the longitudinal direction, and a simulated thermal coating was carried out using a salt bath furnace. The coupons were heated up to 200, 220, and 235°C, kept at these respective temperatures for 5 min, and cooled in air. After heat treatment, full-thickness tensile specimens were taken from the coupons to compare their tensile properties, especially their yield strengths and stress-



(a) Conventional TMCP process



(b) HOP process

Fig. 6 Stress-strain curve before and after coating simulation test

strain curves, with those determined before the coating simulation test. Carbide precipitation during HOP heating is expected to reduce the diffusible carbon atoms. A quantitative chemical analysis of the carbide precipitation was therefore conducted.

**Figure 6** shows longitudinal stress-strain curves of pipes manufactured by conventional TMCP and HOP before and after coating simulation at 220°C. Before the coating simulation test, both showed round-house stress-strain curves without Luders elongation. After the coating simulation heating, the yield strength of the conventional TMCP pipe increased significantly, and Luders elongation appeared in the stress-strain curve. The increase in the yield strength of the HOP treated pipe was very small, the stress-strain curve retained its round-house shape, and the n-value of HOP treated pipe retained high after coating simulation. **Figure 7** shows the effect of the coating temperature on the change in yield strength and *Y*/*T* ratio by the coating simulation test. The yield strength and *Y*/*T* ratio increased after coating simulation for both pipes. The increase in yield strength was very small for the HOP treated pipe, however, and the *Y*/*T* ratio could be kept low enough even at 235°C. The increase of yield strength was presumably caused by the strain aging effect, and the HOP treated pipe presumably resisted the strain-aged hardening by the coating.

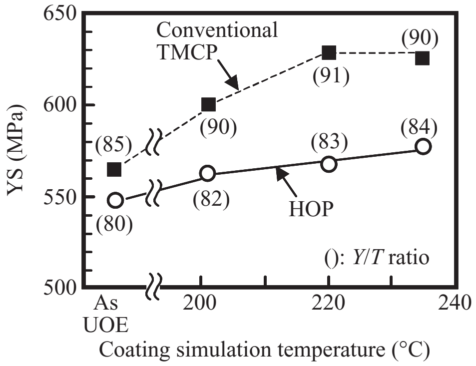


Fig. 7 Effect of simulation heating temperature on yield strength and *Y*/*T* ratio

### 3.3 The Mechanism of Resistance to Strain Aging for New HOP Process Steel

In the previous section, it is cleared that the pipe manufactured by the HOP process, a pipe with a microstructure consisting of bainite and MA, resists strain-aged hardening, and exhibits excellent deformability after thermal coating. As mentioned previously, strain aging is caused by an interaction of dislocation and diffusible carbon atoms.

**Figure 8** shows the results of quantitative chemical analysis of carbide precipitation for both pipes. The amount of carbide precipitation in the HOP treated steel was clearly larger than that in the conventional TMCP steel. Carbide precipitation was presumably formed during the HOP heating. The carbide precipitation consumed diffusible carbon atoms in the bainite phase. Therefore, the amount of diffusible carbon atoms in the HOP treated steel can be assumed to be smaller than that in the conventional TMCP steel. This consumption of diffusible carbon atoms by carbide precipitation conferred the resistance to strain aging and the excellent

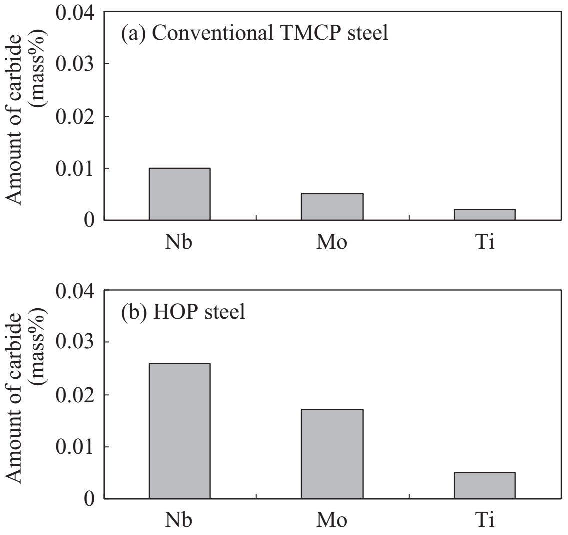


Fig. 8 Results of quantitative chemical analysis of carbide precipitation for both pipes

deformability after the thermal coating.

## 4. Mill Trial Production of X70 to X100 High-Deformability Linepipes with a Bainite-MA Microstructure

### 4.1 Results of Mill Trial Production

Mill trial production of X70 to X100 high-deformability linepipes were carried out based on the aforementioned concept of dual-phase microstructural control. Plates of 14.3 mm to 21.0 mm in thickness were produced by applying HOP, then, used to manufacture pipes with diameters of 762 mm to 1 016 mm by the UOE process. The chemical compositions of the steels for X70 to X100 linepipes are shown in **Table 3**. Low carbon and Nb bearing steels were used. Higher-grade steels have higher ratios of composite C and Mn.

**Photo 2** shows SEM microphotographs of the plates for grade X70 to X100 at the middle-thickness portions. The plate had a bainite microstructure dispersed with MA, and the volume fraction of MA was high enough to improve deformability. **Table 4** shows the longitudinal tensile properties of the pipes produced. All pipes exhibited adequate strength for each grade, a low *Y*/*T* ratio, and a high uniform elongation in the longitudinal direction. **Figure 9** shows longitudinal stress-strain curves for the trial pipes. All pipes exhibited round-house type stress-strain curves.

### 4.2 Results of Mill Coating Test

Next, an actual external FBE coating on a trial X100 linepipe was carried out using a mill coating facility. Three induction coils were used to heat the pipe. The highest temperatures of the outer surface were 200 and 240°C. **Figure 10** shows longitudinal stress-strain curves of the pipes before (as UOE) and after the thermal coating. The pipes after thermal coating exhibited

Table 3 Chemical compositions of the steels for X70 to X100 linepipes

(mass%)

| Grade | C | Si | Mn | P | S | Nb | Other |
|---|---|---|---|---|---|---|---|
| X70 | 0.05 | 0.2 | 1.6 | 0.01 | 0.001 | 0.04 | Cu, Ni, Mo, Ti |
| X80 | 0.06 | 0.2 | 1.8 | 0.01 | 0.001 | 0.04 | Cu, Ni, Mo, Ti |
| X100 | 0.07 | 0.2 | 2.0 | 0.01 | 0.001 | 0.02 | Cu, Ni, Mo, Ti |

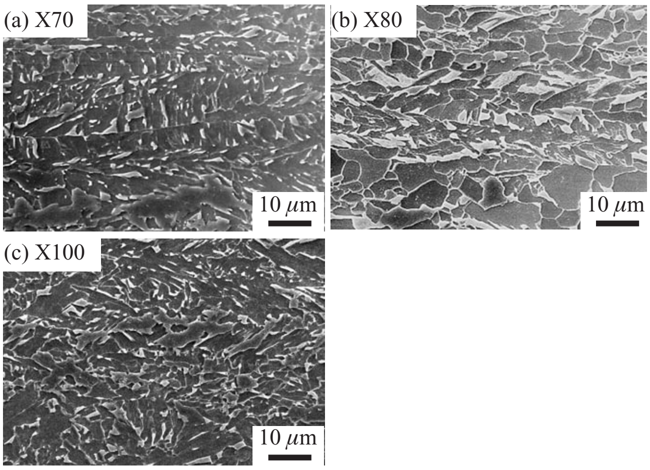


Photo 2 SEM microphotographs of the plates for grade X70 to X100

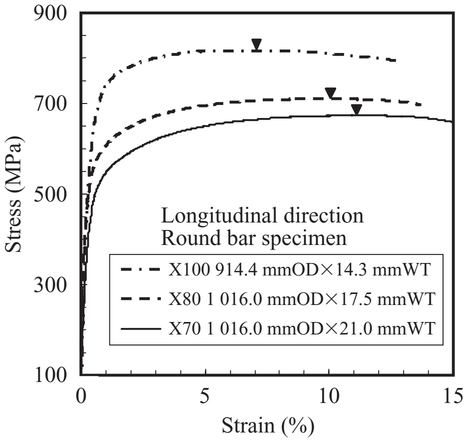


Fig. 9 Longitudinal stress-strain curves for trial production pipes

Table 4 Tensile properties of the trial production pipes

| Grade | Dimention | | | Direction | Tensile properties* | | | |
|---|---|---|---|---|---|---|---|---|
| | OD (mm) | WT (mm) | *D*/*t* (mm) | | YS (MPa) | TS (MPa) | *Y*/*T* (%) | uEl (%) |
| X70 | 1 016.0 | 21.0 | 48 | Longi. | 555 | 669 | 83 | 11.7 |
| | | | | Trans. | 550 | 691 | 80 | — |
| X80 | 1 016.0 | 17.5 | 58 | Longi. | 581 | 734 | 79 | 10.1 |
| | | | | Trans. | 584 | 752 | 78 | — |
| X100 | 914.4 | 14.3 | 64 | Longi. | 658 | 822 | 80 | 6.5 |
| | | | | Trans. | 693 | 843 | 82 | — |

* Requtangular specimen, but uniform elongation (uEl) was measured by round bar specimen.

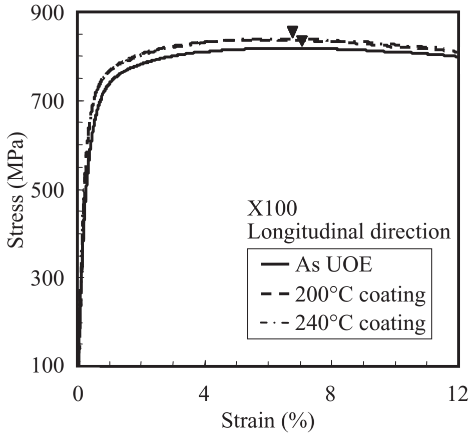


Fig. 10 Longitudinal stress-strain curves for trial X100 linepipes

round-house type stress-strain curves. A higher uniform elongation of over 6% and a lower *Y*/*T* ratio of below 85% were achieved even after coating at 240°C.

## 5. Conclusion

JFE Steel developed high deformability linepipes with resistance to strain-aged hardening. The pipes exhibited a bainite microstructure with finely dispersed MA, high strength, and high deformability. The deformability of the pipes remained high after the application of an external coating. This was because the on-line heat treatment decreased the diffusible carbon atoms, the cause of strain-aged hardening.

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