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Development of High-deformability, High-strength Line Pipes for Ultra-low-temperature Use

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Abstract

Long-distance gas-transmission pipelines from remote areas sometimes traverse discontinuous permafrost, and are subject to ground movement caused by repeated thaw subsidence and frost heave. In this case, a strain-based design has been applied. High grade line pipe with excellent deformability for strain-based design and excellent low temperature toughness is required. This paper describes our progress in this field with regard to metallurgical design and development based on a precise numerical simulation to analyze buckling behavior of line pipe with girth weld. Optimizing chemical composition to suppress the addition of rare earth metal and establishing TMCP conditions optimizing the volume fraction of composite microstructure were performed. Nippon Steel & Sumitomo Metal Corporation has developed high deformable line pipe for stain-based design.

1. Introduction

UOE and spiral-seam steel pipes are used for long-distance pipelines of natural gas. The pipes used for such pipelines in regions of ground movement caused by discontinuous permafrost, landslides, and seismic faults are mostly UOE pipes; they undergo plastic deformation when the ground moves (see **Fig. 1**). Bending and unbending because of thaw subsidence and frost heave of discontinuous permafrost are typical examples of such deformation. Line pipes laid in regions of similar conditions must have strain tolerance or deformation ability to maintain material soundness under expected strain. The design method by which such deformation is anticipated is called strain-based design (SBD).[1)] SBD considers bending deformation and the compressive and tensile strain limits, ε_c and ε_t, of compressive and tensile deformation in the axial direction, respectively. Among these, compressive strain limit ε_c is the strain when a steel pipe locally buckles, and tensile strain limit ε_t is defined in consideration of the allowable defects of girth weld joints when the strain is equal to or greater than ε_c. It follows, therefore, that the enhancement of compressive strain limit ε_c is the most important target in the development of high-deformability steel pipes.

The value of ε_c changes depending on the mechanical properties of steel, such as the stress-strain curve and the geometric imperfection of girth-welded pipes. The mechanical properties parameters that are considered to affect it most are the strain hardening coefficient, plastic anisotropy, and strain aging, and the shape parameters are the longitudinal geometric imperfection (changes in outer diameter and wall thickness), welding deformation of girth weld joints,

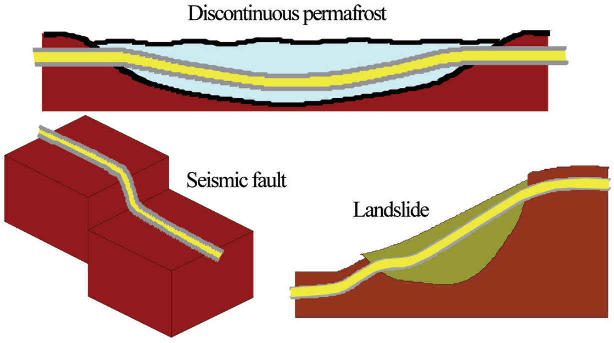

Fig. 1 Pipe deformation with ground movement

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and misalignment of girth welds; the effects of these factors on ε_c have been studied. To quantify these factors affecting ε_c, it is necessary to develop a sophisticated numerical simulation method for analyzing the bending deformation behavior of girth-welded pipes.[2] Such technology constitutes solution technology that increases the reliability of the products of Nippon Steel & Sumitomo Metal Corporation to have them accepted widely, and at the same time, serves as the basis of the material design guidelines for line pipe steel.

According to the concept of SBD, pipelines must be designed such that weld joint failure and pipe buckling does not occur as far as the strain imposed from outside is within a range defined project by project. An important design to prevent the fracture from girth welds is to make the strength of the weld metal overmatch that of the parent pipes in the longitudinal direction. In most cases, coating is applied to line pipes for corrosion protection purposes, and it is necessary to prevent their strength increase caused by strain aging. The lower limit of the strength of the pipes must be the minimum strength of the steel grade specified for the pipeline, and its upper limit below the minimum strength of the weld metal of the joints welded at the construction site. Therefore, it is necessary to select a pipe forming method that can control the pipe strength within the narrow range thus defined. On the other hand, to improve the buckling resistance of pipes under bending moments, the basic measures are to enhance the uniform elongation (U.El) and lower the yield to tensile (Y/T) ratio of the pipes.[3]

It is also necessary to consider low-temperature toughness. Steel pipes must be resistant to both the initiation and growth of cracks. For steel pipes to be resistant to brittle fracture, first, the material must be highly resistant to impacts (having high Charpy absorbed energy) at very low temperatures, and accordingly it is important to optimize the contents of alloy elements; lowering carbon content is one such measure. Another requirement is to arrest crack propagation, if one occurs because of corrosion or human error. For this, it is fundamentally important for the material to fail not by brittle but by ductile fracture at very low temperature ranges below −40°C; forming a fine microstructure is essential for this.

To enhance the four property items, namely low-temperature toughness, deformability, heavy wall thickness, and strength at the same time, Nippon Steel & Sumitomo Metal used to add many expensive and rare alloy elements such as Mo and Ni. The company has since changed the alloy design concept and developed a line pipe product for natural gas pipelines that exhibits the combined properties better than conventional ones with reduced addition of alloy elements. The design concept and characteristics of the developed product are presented below.

2. Factors Affecting Deformability of Line Pipes and Material Design Guidelines

2.1 FEA model of girth-welded pipes and accuracy of deformability estimation

2.1.1 Geometric imperfection model

To analyze the flexural buckling of steel pipes, it is necessary to provide an FEA model with the information of the geometric imperfection in the longitudinal direction. **Figure 2** compares the measured and estimated radius change in the longitudinal direction of girth-welded X80 UOE pipes, 914 mm in outer diameter (D) and 19.6 mm in wall thickness (t); the estimation was conducted using an analysis model. Here, the radius change is composed of the following: a first term Δb, which is the original radius fluctuation of the UOE pipes approximated by a sinusoidal curve; a second term Δg,

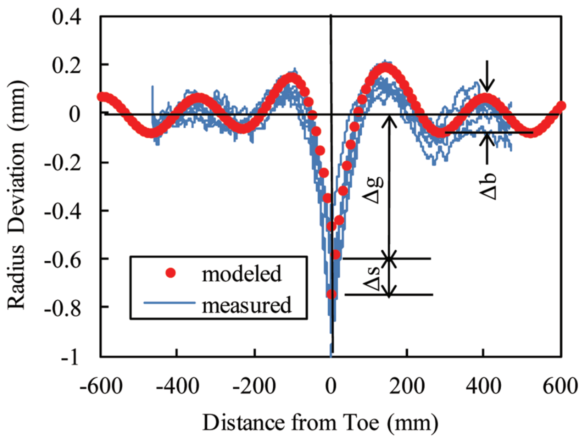

Fig. 2 Radius change in girth-welded UOE pipe

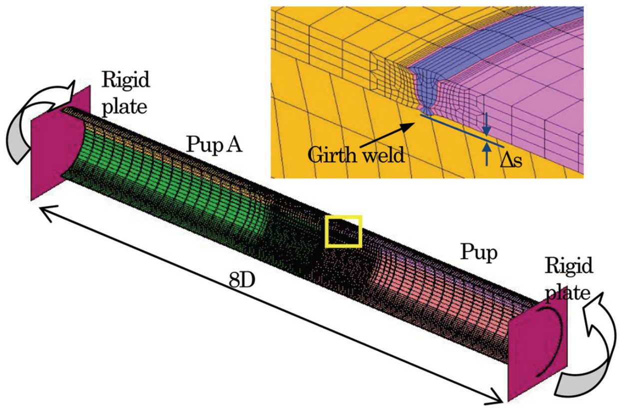

Fig. 3 Bending model for girth-welded pipe

which is the fluctuation caused by the girth welding or the deformation according to Timoshenko's theory of elasticity caused by a moment applied to a pipe end; and a third term Δs caused by the misalignment in the girth welding.[4] UOE pipes intrinsically have radius fluctuation at a certain frequency, and besides this, the diameter is reduced near a girth weld because of the residual stress of the welding. An FEA model of girth-welded pipes reflecting these shape irregularities is given in **Fig. 3**. The flexural buckling strength of steel pipes is evaluated by numerical analysis, under the condition of an internal pressure corresponding to the operating pressure of the pipeline in question and bending moments at both ends; here, the pipes proper, and the welded joint were modeled as three-dimensional solid elements.

2.1.2 Material model

For analyzing the sensitivity of a steel pipe to flexural buckling, it is important to compose the model so as to reflect not only the shape but also the material properties accurately. The SS curves of UOE pipes change, and their plastic anisotropy is accentuated because of the strain during pipe forming and the heating for the coating application, which is often conducted after the shipment from steel works. **Figure 4** shows the SS curves of X80 UOE pipes, 914 mm in outer diameter and 19.6 mm in wall thickness, under tensile stress applied longitudinally (L) and circumferentially (C), before and after the heating to 235°C for 5 min for coating application (as received and aged, respectively, in the graph). The strength of as-re-

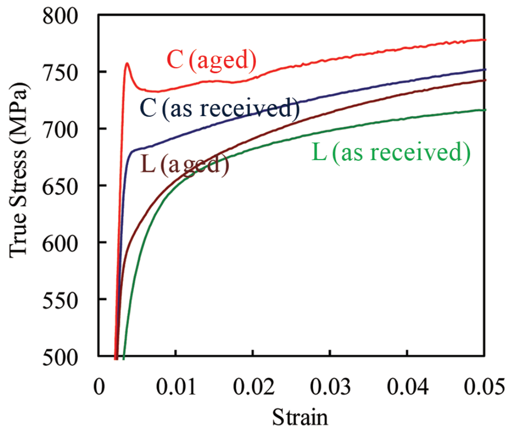

Fig. 4 Plastic anisotropy in UOE pipe

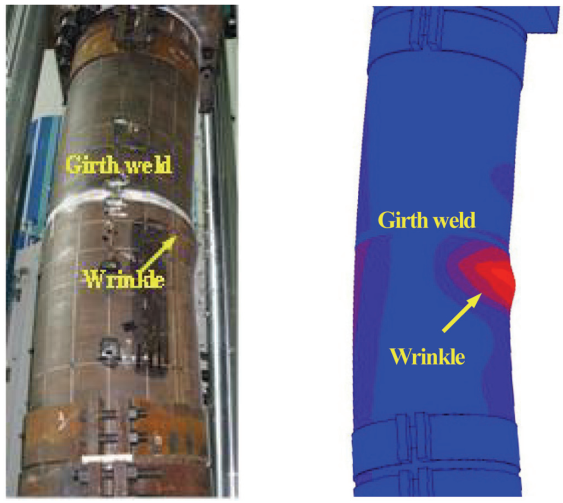

Fig. 5 Buckling behavior of girth-welded pipe under bending and plastic strain distribution

ceived pipes is different in the L and C directions. This difference is called plastic anisotropy; the anisotropy becomes more conspicuous after the heating (aged), and SS curves have different shapes in the L and C directions. While the SS curve in the L direction retains a more or less spherical, yield point elongation is clearly observed in the C direction. No functions have been proposed generally applicable to the yield behavior of a material having different work hardening coefficients in the L and C directions, and it has become possible to analyze the effects of strength anisotropy over the buckling behavior of steel pipes by elaborating a new function applicable to such materials.[5)]

2.1.3 Accuracy of deformation estimation

Figure 5 shows a result of test on the deformability of a steel pipe using full-scale pipes and the result of a deformation simulation using the numerical analysis model mentioned earlier. The full-scale bend test was conducted at C-FER Technology, Canada, using three specimens of the said X80 UOE pipe after heating for coating application and girth welding. Bending load was applied to the specimens under a hydraulic internal pressure equivalent to 72% of the yield stress of the pipes. The bending strain, $\varepsilon_{bend} = \theta / (2\Delta L/D)$, under the maximum bending moment was defined as the compressive strain limit ε_c. Here θ is the bending angle, ΔL the gauge length, and D the outer diameter of the specimen pipes. With girth-welded pipes, local buckling occurred near the welded joint, which agreed well with the results obtained using an FEA model in which the same geometric imperfection and plastic anisotropy were assumed.

Figure 6 compares the compressive strain limits ε_c obtained through the test using full-scale pipes (Exp.) with those obtained through the FEA simulation using the yield function assuming plastic anisotropy (Aniso.) and those assuming plastic isotropy based on the von Mises yield criteria (Iso.). The graph indicates that the estimation agrees well with test results under all conditions when plastic anisotropy is assumed, whereas when plastic isotropy is assumed, the estimated compressive strain limit ε_c tends to be too large. In addition, at the full-scale pipe test, while ε_c did not change significantly through the heating, it decreased by approximately 20% when the pipes were girth-welded.

As stated above, it has been made clear that it is possible to predict the deformability of girth-welded line pipes accurately by modeling the geometric imperfection of the pipes and applying a yield function that considers plastic anisotropy and to analyze the effects of the governing factors of the deformability that were used for the present development.

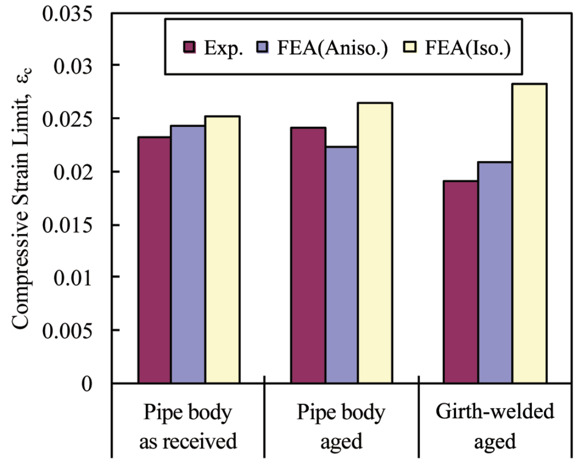

Fig. 6 Comparison of measured and calculated compressive strain limits

2.2 Mechanical properties affecting deformability

2.2.1 Mechanical properties in longitudinal direction

In SBD, the mechanical properties of steel pipes in the longitudinal direction, which is the principal stress direction of bending loads, are specified. In consideration of this, the authors thought of finding the mechanical property item most closely related to compressive strain limit ε_c using the FEA model. They chose 12 specimens of commercially produced X60 steel pipes, 1220 mm in outer diameter and 32.5 mm in wall thickness, drew their SS curves, and from these curves, obtained three mechanical property items of the specimens, namely the Y/T ratio and the flow stress ratios $\sigma_{1\%}/\sigma_{5\%}$ and $\sigma_{1\%}/\sigma_{2\%}$. **Figure 7** shows the correlation of each of these property items with the compressive strain limit ε_c of the pipes under an internal pressure equivalent to 40% of the yield stress. In overseas pipeline projects, Y/T and $\sigma_{1\%}/\sigma_{2\%}$ have been used for SBD. Under the conditions of the present study, however, $\sigma_{1\%}/\sigma_{5\%}$ proved to have the closest correlation with the compressive strain limit ε_c. This is presumably because the local strain at the start of buckling is 5%. Therefore, increase in $\sigma_{1\%}/\sigma_{5\%}$ was set forth as the guideline for the development of material for high-deformability line pipes.

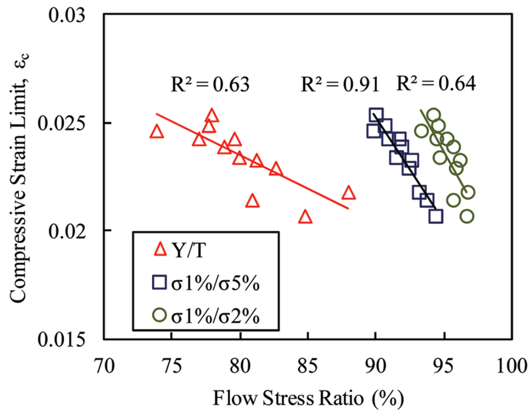

Fig. 7 Correlation between compressive strain limit and mechanical property factors

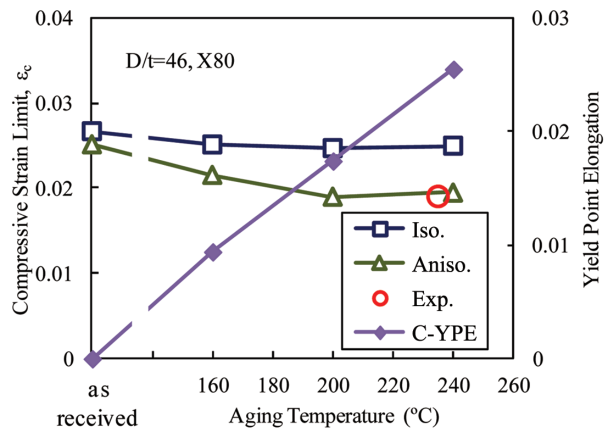

Fig. 8 Effect of C-YPE on compressive strain limit

2.2.2 Mechanical properties in circumferential direction

The yield point elongation seen in the SS curves in the longitudinal direction of line pipes after the heating for coating application has been known to deteriorate the bending deformability. Therefore, the authors aimed at increasing the work-hardening coefficient of steel, and at the same time, making its SS curve as round as possible. At that time, however, the effects of the yield point elongation in the SS curve in the circumferential direction over the compressive strain limit ε_c were unclear. The compressive strain limits of pipes aged at different temperatures were calculated from respective SS curves using FEA, wherein a model assuming plastic isotropy (of Iso. in Fig. 6) and another assuming plastic anisotropy (of Aniso. in Fig. 6) were used. In addition, the pipes were assumed to be under an internal pressure equivalent to 72% of the yield stress. **Figure 8** compares the compressive strain limits thus obtained. A curve of the yield point elongation in the circumferential direction (*C-YPE*) of pipes aged at different temperatures is also given in the graph. It has to be noted here that all SS curves in the longitudinal direction were round. The graph shows that when plastic anisotropy is assumed, the compressive strain limit decreases as the heating temperature increases, and in the range of 200°C and above, it remains unchanged; however, when plastic isotropy is assumed such decrease in the compressive strain limit is not observed. Judging from the indications that, with the isotropic hardening model, the compressive strain limit does not change depending on the heating temperature and that the result obtained using the anisotropic hardening model agreed well with the test result using full-scale pipes, the decrease in the compressive strain limit ε_c is considered to result from the *C-YPE*, which increases with increasing heating temperature.

As explained above, it has been made clear that the stress-strain behavior of line pipes in both the longitudinal and circumferential directions affects their buckling characteristics.

2.2.3 Effects of steel strength fluctuation

The strength of commercially manufactured steel pipes fluctuates within an allowable range under applicable standards. As a result, the strength of a completed pipeline may be different across a girth weld. Thus, in addition to the geometric imperfection caused by welding, there may be a change in the strength near a weld joint, and consequently local buckling may occur there.

Figure 9 shows the relationship between the compressive strain limit ε_c and the difference in the yield strengths ΔYS of two line pipes welded together at a joint. In the analysis, the internal pressure was changed to a maximum of 72% of the yield stress, and axial

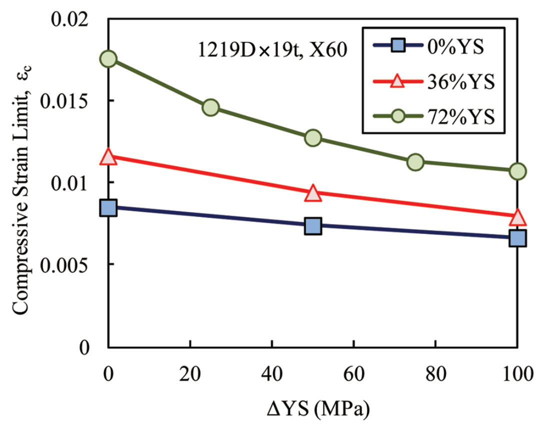

Fig. 9 Effect of strength mismatch on compressive strain limit

strain was arrested. Under any condition, the compressive strain limit decreased with increasing ΔYS, and the decrease was more significant as either the internal pressure or the initial compressive strain limit increased. This result points to the importance of pipeline design considering the strength fluctuation of the pipes in addition to the material properties in the plasticity design of pipelines such as SBD. Therefore, steelmakers are requested to minimize the strength fluctuation of line pipes.

2.3 Quantifying geometric imperfection components affecting deformability

The effects of each component (given in Fig. 2) of the geometric imperfection and those of the difference in the pipe strength over the compressive strain limit ε_c are quantified in **Fig. 10**. Here, the specimens are X80 pipes 762 mm in outer diameter and 15.8 mm in wall thickness under an internal pressure equivalent to 72% of the yield stress. The condition for the column ΔYS, given as the reference, is that there is no geometric imperfection except for the girth weld, and the strength difference ΔYS between the two pipes is 50 MPa. The maximum decrease in the compressive strain limit ε_c caused by the synergistic effects of the geometric imperfection components (the diameter shrinkage due to welding Δg, original pipe diameter fluctuation Δb, and the weld joint misalignment Δs) was 17%. In contrast, that caused by the pipe strength difference (ΔYS = 50 MPa) was estimated at 28%, which indicates that the decrease in the compressive strain limit due to pipe strength difference is presumably larger than that due to geometric imperfection.

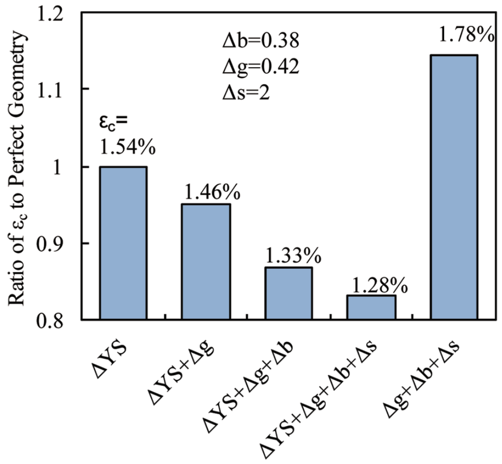

Fig. 10 Combined effect of geometric imperfection and strength mismatch on compressive strain limit

As seen above, it is possible to predict the lower limit performance of girth-welded UOE line pipes by tests using full-scale pipes and numerical simulation of their deformation behavior, which will significantly contribute to improving the safety and reliability of pipelines through SBD.

3. Development of High-deformability Line Pipes

The above study has made it clear that to produce line pipes of high deformability it is necessary to develop material steel plates aiming at the following:

1) Maximizing the work hardenability in the longitudinal direction;
2) Minimizing the yield point elongation in the circumferential direction; and
3) Minimizing the strength difference between pipes.

Thus, the development activities of high-deformability line pipes were under these guidelines.

3.1 Design concept of material steel

First, the design concept of steel for the present development is explained. To obtain good deformability, a composite structure of soft ferrite and hard bainite excellent in work hardenability was selected as the microstructure. Then, in consideration of the use in very cold regions and to ensure good toughness at temperatures as low as −40°C, a fine composite structure, of an average crystal grain size of 5 μm or less (by the ASTM measurement method), was aimed at. The following three unprecedented characteristics were envisaged in the development of the high-deformability line pipes.

The first was elimination of Mo, which had been an indispensable alloying element for line pipes, to improve the deformability after the heating for coating application. In general, line pipes undergo strain aging when heated to 200°C or above. The more the free carbon, the more easily the strain aging occurs, leading to higher Y/T ratio, lower U.El, and consequently lower deformability. In this relation, the authors discovered for the first time in the world that when steel did not contain Mo, considerable quantity of cementite was formed, the amount of free carbon decreased significantly, and as a result deformability was improved.

Figure 11 compares steels with and without Mo addition in terms of the increase in yield strength after applying 1% pre-strain and then strain aging at 240°C.[6, 7] The increase in the yield strength of the Mo-free steel after the aging is markedly smaller than that of the steel containing Mo. **Figure 12** shows the microstructures of the Mo-free and Mo-containing steels before the aging was observed through a transmission electron microscope;[6, 8] the amount of cementite in the Mo-free steel was greater than that of the Mo-containing steel. Note here that the hardenability index β[9] was substantially the same in the two steels and so was the γ to α transformation commencement temperature. It has been known that because transformation stasis is often observed with steel containing Mo,[10] when such steel is cooled from the stasis state to room temperature, a non-transformed γ phase and martensite form. This is also the case with the present study. While there was a non-transformed γ phase and martensite in the Mo-containing steel, it was presumed that these phases did not form in large quantities in the Mo-free steel; instead, considerable amount of cementite formed.

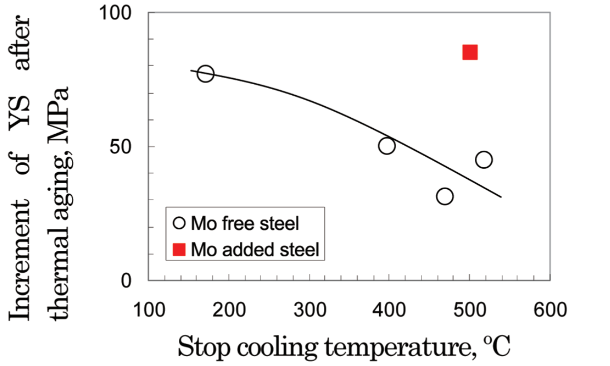

Fig. 11 Increase in YS of Mo-free and Mo-containing steels after application of 1% pre-strain and aging at 240°C[6, 7]

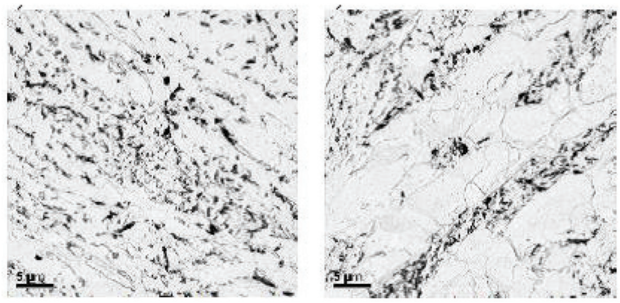

Fig. 12 TEM images of Mo-free and Mo-containing steels (left and right, respectively, in replicas)[6, 8]

The second envisaged characteristic is strength fluctuation within a limited range through effective use of the accelerated cooling process, called the continuous on-line control-μ (CLC-μ), which serves to compensate the decrease in strength because of the absence of Mo and realize homogeneous cooling at an accurately controlled rate. Therefore, a mild accelerated cooling (MAC) process has been established as a unique in-house technology to continuously and accurately control the volume fractions of ferrite and bainite as desired even under the conditions of commercial mass production; **Fig. 13** schematically shows the concept of the mild cooling process.[6, 7] As a result, the tensile strength of steel plates under the same specifications has been confined within a range of 50 MPa.

The third characteristic envisaged is to obtain an ultra-fine microstructure having an average grain size of 3 μm or less (by the ASTM measurement method) to secure high toughness at very low temperatures. This was achieved by optimally controlling the operating conditions of the plate rolling processes and precise control of the accelerated cooling to realize homogeneous cooling. **Figure 14** shows a typical microstructure of the steel thus manufactured, taken using a scanning electron microscope.[6, 11)]

It has become possible to manufacture high-deformability line pipes in accordance with the specifications of API X60 to X100 using plates of Mo-free steel containing a minimum required amount of Ni and processed through the precision cooling process. It has to be noted in this relation that X100 pipes having a composite structure of soft ferrite and hard bainite and containing a martensite-austenite constituent (M-A) by a controlled amount is being developed (see **Fig. 15**).[12)] However, active use of the M-A adversely affects the toughness of the heat-affected zones of weld joints, and it is necessary to carefully control its amount.

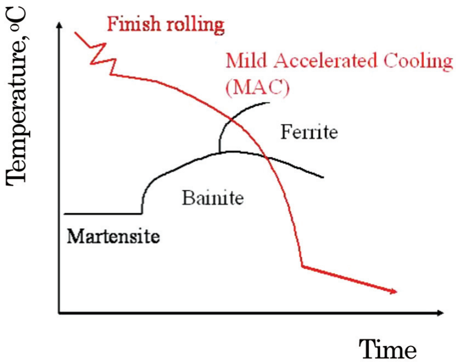

Fig. 13 Cooling curve during accelerated cooling[6, 7)]

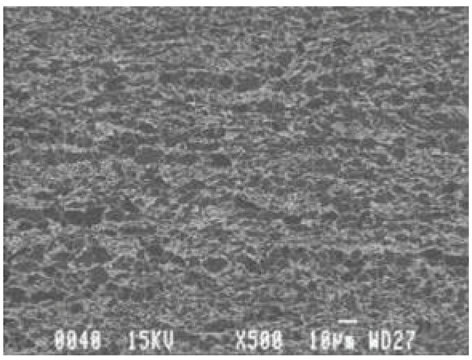

Fig. 14 SEM image showing microstructure of highly deformable pipe[6, 11)]

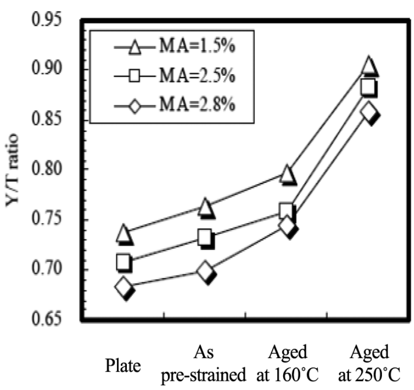

Fig. 15 Effect of M-A content on yield to tensile ratio[12)]

3.2 Properties of developed steel

High-deformability pipes of API X60 were manufactured for a pipeline project in Russia. The mechanical properties of the pipes before and after strain aging are explained here. **Figure 16** shows the *Y*/*T* ratio and the U.El before and after strain aging at 240°C:[6, 11)] the *Y*/*T* ratio was 88% or less before and after the aging, and the U.El was 10% or more. As for low-temperature toughness, ultra-fine microstructure of an average crystal grain size of 3 μm or less was obtained by adequately controlling the operation conditions of the plate rolling processes to secure a satisfactory toughness at a very low temperature of −40°C. **Figure 17** shows the ductile-brittle transition curve of the same pipes at drop weight tear test (DWTT).[6, 11)] Although it is usually very difficult to obtain a high ratio of ductile fracture at DWTT with steel pipes of wall thickness as large as 32 mm, the developed pipes achieved 85% ductile fracture at as low a temperature as −60°C owing to the fine-grain microstructure.

3.3 Actual application references

Based on the developed high-deformability technology, line pipes of API X60 to X100 for natural gas pipelines containing alloy elements by minimum amounts have been manufactured and launched to the market. 17000 t of API X 60 pipes were produced for a Russian pipeline in 2009 (see **Fig. 18**),[6, 11)] and API X100 pipes were laid across a distance of 5 km in Canada.[6, 13)] More recently, Nippon Steel & Sumitomo Metal received an order for 5000 t of API X70 pipes for a pipeline project in Myanmar and has completed manufacturing.[14)]

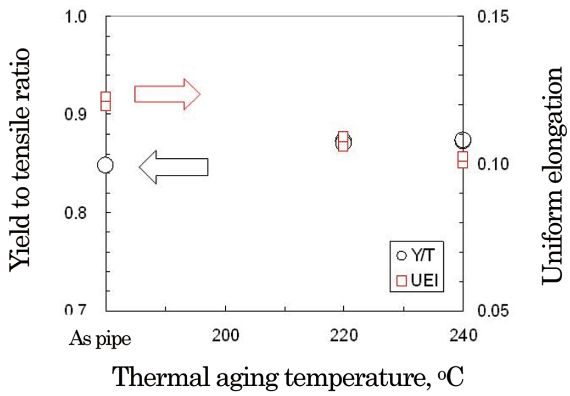

Fig. 16 Mechanical properties before and after thermal aging of API grade X60 highly deformable pipe[6, 11)]

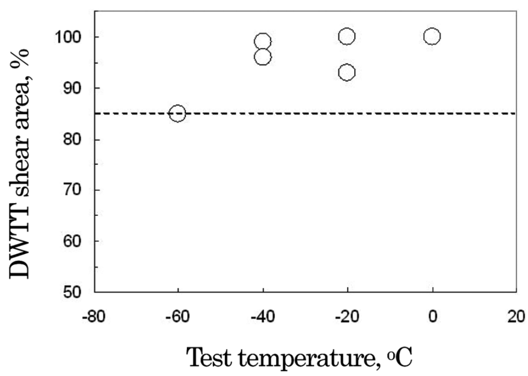

Fig. 17 DWTT properties of API grade X60 highly deformable pipe[6, 11)]

Fig. 18 Field construction line of API X60 high-deformability linepipes [6]

4. Closing

To develop steel pipes for natural gas pipelines capable of withstanding plastic deformation, it is essential to prepare a new pipe material that tolerates deformation, and in addition, establish a solution technology to verify the reliability of the performance of the developed product. Nippon Steel & Sumitomo Metal has successfully developed and commercialized high-deformability UOE line pipes by effectively combining these technologies. The fruits of R&D activities that paved the road to the success were as follows:

(1) A mathematical analysis model considering the geometric imperfection and plastic anisotropy of girth-welded UOE pipes has been worked out, which model has, in analyses of flexural buckling of girth-welded steel pipes, yielded results in good agreement with the buckling limits obtained through tests using full-scale pipes.

(2) Based on sensitivity analysis using the developed model, the material and shape factors that govern the buckling resistance of line pipes have been quantitatively defined, and thus it has been made possible to estimate the lower limit of the compressive strain limit.

(3) Based on the quantification of the factors that determine deformability, the conditions have been defined for the precision cooling of heavy steel plates containing minimum amounts of rare metal elements required to obtain a composite microstructure excellent in deformability, which led to the successful development of high-deformability line pipes for natural gas transport in very cold regions.

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