International Symposium on Microalloyed Steels for the Oil and Gas Industry
Edited by W.J. Fazackerley, P. Bordignon, K. Hulka, and F. Siciliano
TMS (The Minerals, Metals & Materials Society), 2007

HIGH DEFORMABILITY UOE LINEPIPES PRODUCED BY ADVANCED TMCP TECHNOLOGY

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Keywords: High strength linepipe, Deformability, TMCP, Dual-phase microstructure.

Abstract

Extensive studies to develop high deformability linepipe have been conducted. In case of linepipes laid in a seismic region, higher resistance to buckling against large strains induced by earthquake related ground movement is required. In order to improve the deformability of pipes, two different types of microstructural control technologies were proposed, based on theoretical and analytical studies on the effect of microstructural characteristics on stress-strain behavior. Grade X65 to X100 linepipes with ferrite-bainite microstructure were manufactured by optimizing the microstructural characteristics. Grade X80 linepipe with bainitic microstructure containing dispersed fine M-A constituents was also developed by applying new conceptual TMCP process. Deformability of developed linepipes with two different types of microstructure was evaluated by axial compression and bending tests, and all the developed linepipes showed superior resistance to buckling comparing with conventional pipes.

Tensile properties after thermal coating of developed high deformability pipe were also investigated. It was shown that an increase in yield strength by thermal strain aging was minimized and a roundhouse type stress-strain curve was maintained for the linepipe manufactured by the new conceptual TMCP process.

Introduction

Recent studies [1] indicate the significant economical advantages of using higher grade linepipes in constructing long distance pipelines. Those advantages can be shown by increasing transportation efficiency of pipelines and reducing material costs. The thinner wall materials bring lower total tonnage of material itself and fabrication costs for girth welding. Accordingly, the application of high strength linepipes such as API X70 or X80 grades have been increased in recent years, and X100 was put to practical use for the first time in 2002[2].

On the other hand, construction of pipelines has expanded to the environmentally severe regions such as the arctic, seismic regions, deepwater and sour gas environments. Various material properties in addition to higher strength, such as toughness, deformability and sour resistant properties, are required for more recent linepipe steels. Thermo-Mechanical Controlled Processing (TMCP) technologies for producing high strength steel plates have been developed driven by the needs for more severe linepipe use. The accelerated cooling process is the most important technique for improving strength and toughness. Precise microstructural control by the TMCP process enables the required material properties required of linepipes to be obtained.

One of the most challenging fields for pipeline development is thought to be the seismic and permafrost regions where large plastic deformation is expected to be introduced to buried pipelines. New design methodology, so called "strain-based design", for the pipeline engineering in seismic and permafrost regions has been developed [3-5], and high strain linepipe applications have been enabled by this new design concept. According to the concept, higher resistance of pipe to the larger compressive and tensile strains is required. Stringent control of yield strength range of pipe is also important to allow for over-matching of the girth welds.

Complying with this tendency, extensive studies to develop high strength linepipes with higher deformability have been conducted. It is said that deformability of the steel pipes is improved by increasing strain hardenability (lowering yield to tensile ratio) of the steel. The strain hardenability is strongly affected by the microstructure of the steel [6]. Since dual-phase microstructures consisting of harder and softer phases are essential to obtain larger strain hardenability and resulting higher deformability, the optimum microstructural characteristics for higher deformability were investigated by analytical methods which can simulate microscopic behavior of the dual-phase steels.

According to the analysis results, two types of high deformability linepipes which have ferrite-bainite and bainite–martensite (MA) dual-phase microstructure have been developed. Those linepipes have higher resistance to buckling and fracture from the large strains induced by ground movement.

In this paper, the mechanical and metallurgical characteristics of recently developed high strength UOE linepipes and manufacturing technologies are introduced.

Manufacturing Technology of Steel Plate for Linepipe

Accelerated Cooling (ACC) Technology

Controlled rolling and accelerated cooling processing is usually applied in the production of high strength steel plate for linepipe, especially, to secure toughness and weldability as well as high strength. JFE Steel has extensive experience in TMCP (Thermo-mechanical controlled processing) technology, and the application of the accelerated cooling process to heavy gauge steel plate production. This was put to practical use in the Fukuyama plate mill for the first time in the world in 1980[7]. In 1998, "Super-OLAC" (on-line accelerated cooling device) was developed and installed in the Fukuyama plate mill, where the highest cooling rate was achieved by a new water flow control technology in 1998[8]. Higher cooling rate in accelerated cooling is effective to obtain not only high strength by transformation strengthening but also high toughness by refinement of transformed microstructure, and this gives the benefit of producing high strength, high toughness steels with reduced alloying additions.

Plate for the high deformability linepipe steel with ferrite-bainite microstructure is available by precise temperature control in ACC stage. Because strict microstructural control is needed to achieve high deformability, this precise temperature control is essential to produce the high deformable linepipe. To meet this requirement, the Super-OLAC system has been applied. Temperature differentials in a plate after ACC are much smaller than that of the old systems. This brings higher strength plates with lean alloying additions and uniformity within the plates for both mechanical properties and shape.

On-line heat treatment technology

As mentioned above, various and precise material design depending on the application of the linepipe is needed in response to diversified demands for recent pipelines, such as sour resistance and deformability in addition to strength and toughness. In order to produce such high strength and high performance linepipe steels, online heat-treatment processing, HOP (heat treatment on-line process), was installed in Fukuyama plate mill in the West Japan works [8]. HOP is the solenoid type induction heating equipment that is set on the production line adjacent to a hot leveler and behind the accelerated cooling device, (Super-OLAC). In combination with Super-OLAC and HOP has enabled novel metallurgical controlling that cannot be achieved by the conventional TMCP process. One example of the temperature profile when steel plate is manufactured applying HOP is shown in Figure 1 together with the conventional TMCP process. In the conventional TMCP process, the steel plate is controlled rolled and accelerated cooled and then cooled in the air. Employing the HOP applied process; the plate is rapidly heated by the induction coils immediately after accelerated cooling. As a result, various characteristics are obtained by controlling transformation, carbide precipitation and second phase formation at the same time that cannot be achieved by the conventional process. Examples of the linepipe applied by the HOP process are high strength sour linepipe, high deformability linepipe and high strength pipes for the use in conductor casings and risers. Homogeneous material properties in the through thickness direction as well as longitudinal and transverse direction of the plate are obtained by HOP processing, resulting in a smaller scatter of mechanical properties in the mass production and excellent pipe dimensional control which is represented by lower out-of-roundness. Moreover, thermal stability of the material properties are increased by the HOP process and this improves heat resistance, such as SR (stress relief) heat-treatment, and resistance to strain aging.

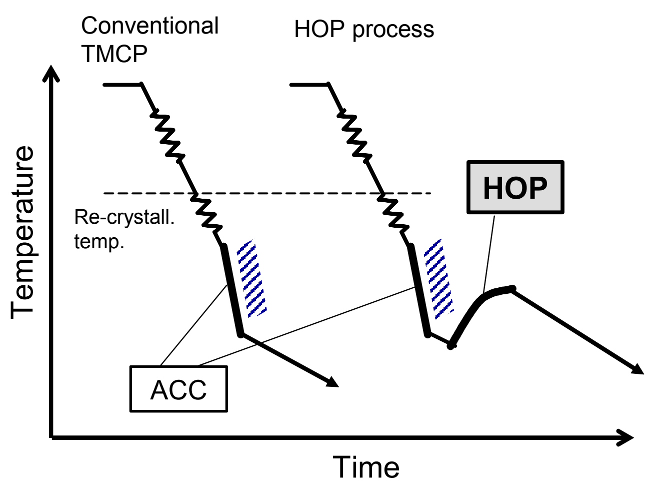


Figure 1. Schematic temperature profile during the plate production process.

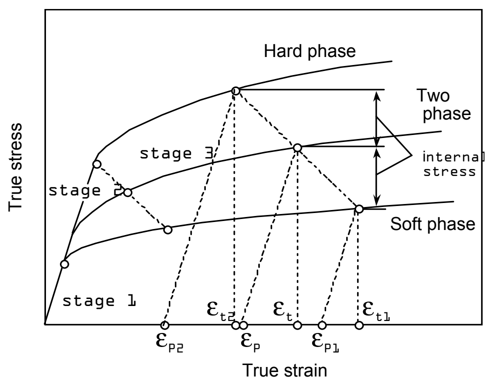
Stress-strain curve control technology for deformability

Prediction of Work Hardening behavior of Dual-Phase Steels by Micromechanics

In order to investigate the effect of microstructural characteristics on work hardening properties of dual-phase (DP) steels, the theoretical model so called "Micromechanics" was applied [9]. This continuum model is based on Eshelby's inclusion theory, the Mori-Tanaka's mean field concept and the von Mises type plastic flow rule. By using this model, the flow stress of dual-phase materials can be estimated from the stress-strain relationship of each constituent phase. In order to calculate the macroscopic stress-strain curves of DP steels, each composite should be given in the form of a numerical equation. The main stress-strain equation used in the continuum plastic theory is the Swift's equation;

$$\sigma_i = a_i (b_i + \varepsilon_{pi})^{Ni} \tag{1}$$

where *i* means *i*th phase. *i* is 1 for the softer phase and is 2 for the harder phase in this paper.
The stress-strain relationship of dual phase materials can be divided in three stages, which are defined below and shown in Figure 2.



Stage I: The two constituent phases deform elastically
Stage II: The softer phase deforms plastically, the harder phase continues to deform elastically
Stage III: Both phases deform plastically

Figure 2. Stress-strain curves of two phase material, hard and soft phases showing the 3 stages of the model.

When an applied uni-axial tensile stress σ^A_{33} reaches the yield strength of the softer phase, σ^I_y, the softer phase starts to deform plastically. The macroscopic yield stress of the DP steel is equal to σ^I_y. As the plastic deformation proceeds in the softer phase, the discontinuities of the plastic strain at the boundary of the two phases increases. This leads to the internal stress, which hinders the further plastic flow in the softer phase and aids the onset of the plastic flow in the harder phase with σ^A_{33} less than the yield stress of the harder phase. At stage II, a stress-strain curve of a two phase material can be written as:

$$\sigma^A_{33} = \sigma_1 [\varepsilon_{pl}] + f F \varepsilon_{pl} \tag{2}$$

where ε_{pl}, $\sigma_1 [\varepsilon_{pl}]$ and f are the plastic strain of the softer phase, a flow stress curve of the softer phase and volume fraction of the harder phase, respectively. Factor F is a function of the shape of the harder phase and elastic constants and the equal to $E(7- 5\nu)/\{10 (1 - \nu^2)\}$ in case of spherical grains. Using the above model, the effect of the strength difference between the hard phase and soft phase and the effect of volume fraction of soft phase were investigated for three types of DP steels. In all the models, ferrite phase was set as the soft phase, and as the hard phase, pearlite, bainite and/or martensite was selected. Stress-strain curves for each constituent phase were experimentally measured and expressed by equation (1). Analysis results on n-value in the stage II was plotted against tensile strength difference in Figure 3. *n*-value increases with increasing strength difference and with increasing volume fraction of hard phase. Ferrite-bainite steels showed higher n-values than ferrite-pearlite steel, while ferrite-martensite steels have highest n-value. Higher n-values, more than 0.1, can be obtained for the ferrite-bainite steels when the bainite fraction is more than 30%. However, 10% of the hard phase is enough for ferrite-martensite steel to obtain the same n-value as ferrite-30% bainite steels.

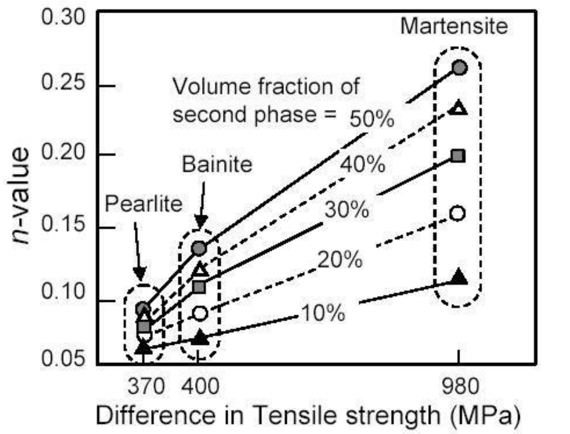


Figure 3. Effect of difference in strength on work hardening behavior of two-phase steels.

<ins>Finite Element Unit-Cell model</ins>

Micromechanics is a useful tool for estimating stress-strain behavior of DP steels. However, it is based on the inclusion theory and the hard second phase is treated as a spherical particle. Therefore, close examination of the effect of morphology on the second phase was conducted using finite element unit cell model. Socrate and Boyce[10] and Ishikawa et al.[11] proposed micro-mechanical models based on a staggered array of particles. In this model, a truncated octahedron, the Voronoi cell on a regular BCC lattice was used. Because of the periodical symmetry, only half of this Voronoi cell is used for analysis, and this can be treated as axisymmetric unit cell which contains the second phase particles. Figure 3(b) shows two adjacent axisymmetric unit Voronoi cells. Height of the unit cell was set as H_0=1 in the analysis. Geometric compatibility of the deformation in the two anti-symmetric cells requires the constraint of the radial and axial displacement of outer boundary as follows,

$$[R_0(\xi)+U_r(\xi)]^2+[R_0(1-\xi)+U_r(1-\xi)]^2=2[R_0|_{0.5}+U_r|_{0.5}]^2 \quad (4)$$

$$U_z(\xi)+U_z(1-\xi)=2U_z|_{0.5} \quad (5)$$

where, $U_r(\xi)$ and $U_z(\xi)$ are the radial and axial displacement of the outer boundary at $z=x$. These boundary conditions are one of the significant features of the V-BCC model, which is less constrained than conventional models and large plastic flow can be allowed in the matrix material. For a detailed explanation for the V-BCC model, refer to Socrate and Byce[10].

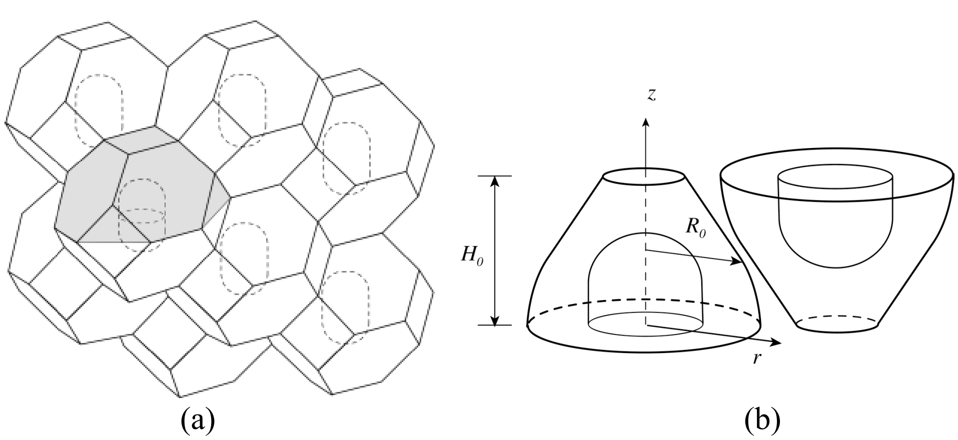


Figure 3b. The V-BCC model: (a) three dimensional array of Voronoi tessellation of the BCC lattice, (b) two adjacent axisymmetric V-BCC cells.

Stress-Strain Behavior of Ferrite-Bainite Steels

The ferrite-bainite microstructure was selected for the analysis because a higher n-value was obtained in the experimentation. The FE program ABAQUS ver.5.8 was used for the analysis. The V-BCC cells were modeled using axisymmetric second-order elements. Figure 4 shows examples of the finite element meshes for the ferrite-bainite microstructure with the bainite volume fraction of 30% and bainite aspect ratio of 1.0 and 4.0. The stress-strain relation of each constituent phase was obtained experimentally. The bainite volume fraction and bainite aspect ratio were changed in order to investigate the effect of microstructural characteristics.

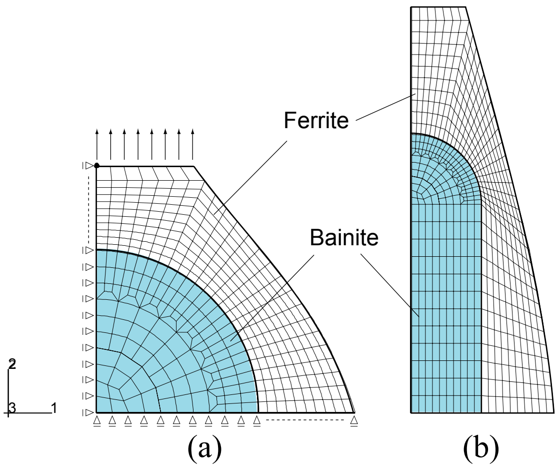


Figure 4. Finite element meshes for ferrite-bainite steels: (a) bainite aspect ratio, Ra=1.0, (b) Ra=4.0

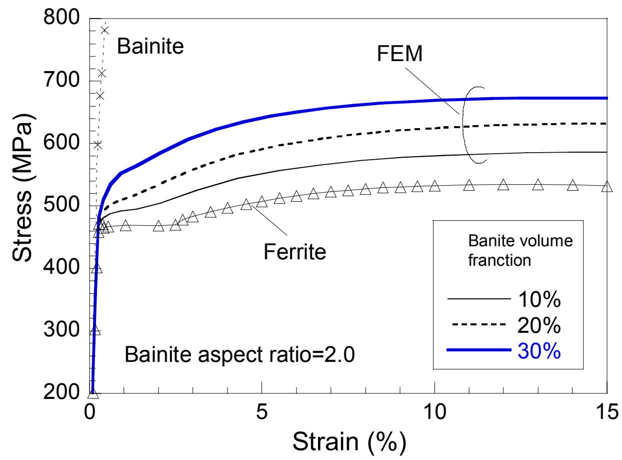
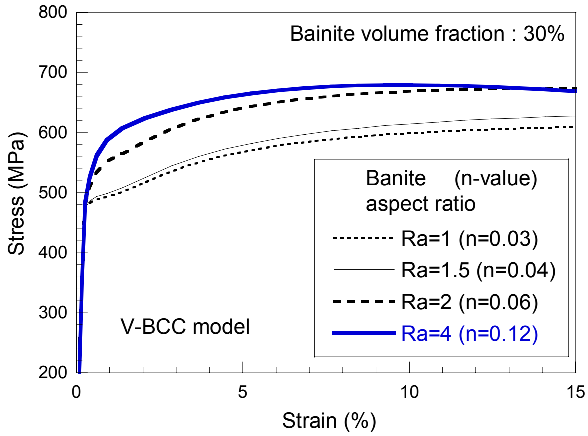


Figure 5. Effect of bainite volume fraction on stress-strain curves for the ferrite-bainite steels with bainite aspect ratio of Ra=2.0

Figure 5 shows nominal stress-nominal strain curves of a ferrite-bainite steel with different bainite volume fractions obtained by the V-BCC model. Bainite aspect ratio, Ra, was 2.0. Ferrite phase itself has a Luders elongation; however, Luders elongation became small as bainite volume fraction increased. And Round-house type stress-strain curve was obtained by a bainite volume fraction of 30%. Fig. 6 shows the effect of bainite aspect ratio on stress-strain curves. The stress value in the smaller strain range after yielding increased largely by increasing bainite aspect ratio, and n-value evaluated in the strain range from 1.0% to 4.0% increased largely. And almost the same stress-strain curve was obtained when Ra=4.0. Local distribution of equivalent strain inside each phase in the case of Ra=1.0 and 4.0 are shown in Fig. 7. Large strain concentration can be seen in the ferrite phase around the top of the elongated bainite for the ferrite-bainite with Ra=4.0. Because of the constraint by the long side boundary of elongated bainite, plastic straining in the ferrite phase is enhanced around the top of the bainite phase. This can be the reason for higher stress after yielding and a higher n-value. Therefore, it was suggested that ferrite-bainite steels with elongated bainite showed Round-house type stress-strain curves with higher n-values.



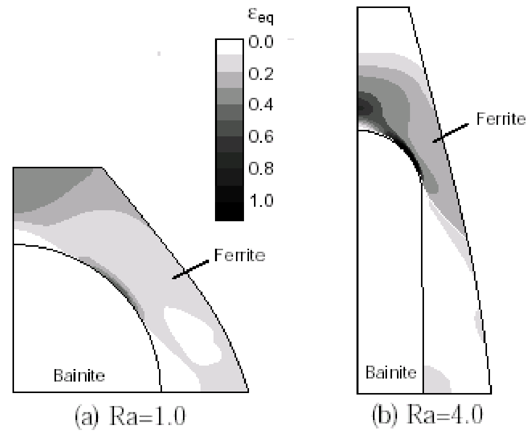


Figure 6. Finite element meshes for ferrite-bainite steels: (a) bainite aspect ratio, Ra=1.0, (b) Ra=4.0

Figure 7. Effect of bainite volume fraction on stress-strain curves for the ferrite-bainite steels with bainite aspect ratio of Ra=2.0

Development of High Strength Linepipes with Superior Deformability

High Deformability Linepipes with Ferrite-Bainite Microstructure

Based on the above considerations on controlling microstructure, high strength linepipes were developed, aimed at having higher deformability for resistance to buckling. TMCP conditions, such as controlled rolling and accelerated cooling, were optimized in order to obtain the ferrite-bainite microstructure with elongated bainite. Table 1 shows examples of API Grade X65-X100 linepipes developed. All steels have a ferrite-bainite microstructure which was obtained by applying controlled rolling followed by accelerated cooling processing. Figure 6 shows an example of the microstructure of the developed high deformability linepipe, compared with conventional linepipe. The newly developed linepipe has a ferrite-bainite dual phase microstructure, while conventional linepipe shows a bainite single phase. Microstructural characteristics of developed high deformability linepipes were carefully controlled by controlling the chemical composition and plate manufacturing parameters, resulting in balancing higher strength and higher n-value and at the same time a lower Y/T ratio in the longitudinal direction of the pipe.

Table 1. Mechanical properties of the high deformability linepipes with ferrite-bainite microstructure.

Grade	Dimention			Tensile properties [1)]				Impact properties	
	OD (mm)	WT (mm)	D/T	YS (MPa)	TS (MPa)	Y/T (%)	n	vE_{-10} (J)	vTrs (^{o}C)
X65	762.0	19.1	40	463	590	78	0.16	271	-98
X80	610.0	12.7	48	553	752	74	0.21	264	-105
X100	914.4	15.0	61	651	886	73	0.18	210	-143

[1)] Longitudinal direction

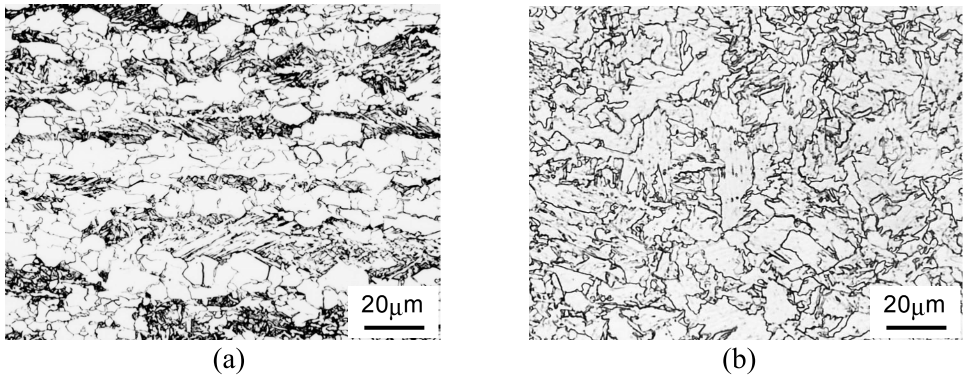


Figure 6. Microstructure of X65 grade linepipes: (a) high deformability linepipe with ferrite-bainite microstructure, (b) conventional linepipe.

High Deformability Linepipes with Bainitic Microstructure Containing Dispersed Fine M-A Constituents

As discussed in the previous section, dual-phase microstructures which contain a harder second phase, such as martensite, shows higher n-values even with a relatively small amount of hard phase. In order to obtain a dual phase microstructure containing martensite-austenite constituents (MA), a new microstructure controlling process was developed, by applying a heating process after the accelerated cooling process. Figure 8 shows the schematic illustration of the new microstructure controlling process. This process consists of three stages. Accelerated cooling (ACC) is stopped above the bainite transformation finishing temperature, where untransformed austenite remains. At this stage, the microstructure is bainite and untransformed austenite. Immediately after ACC, heat treatment is applied by using the on-line heating device. During the heating, carbon in bainite diffuses into austenite. After the heating, austenite with a higher carbon content is retained, and this can form MA by air cooling, because of the existence of highly concentrated carbon in the austenite. Volume fraction of MA is affected by chemical composition of the steel and ACC and heating conditions. Figure 9 shows the effect of volume fraction of MA on Y/T ratio of steel where the new process described above was applied. By increasing the volume fraction of MA above 5%, the Y/T ratio falls below 80%.

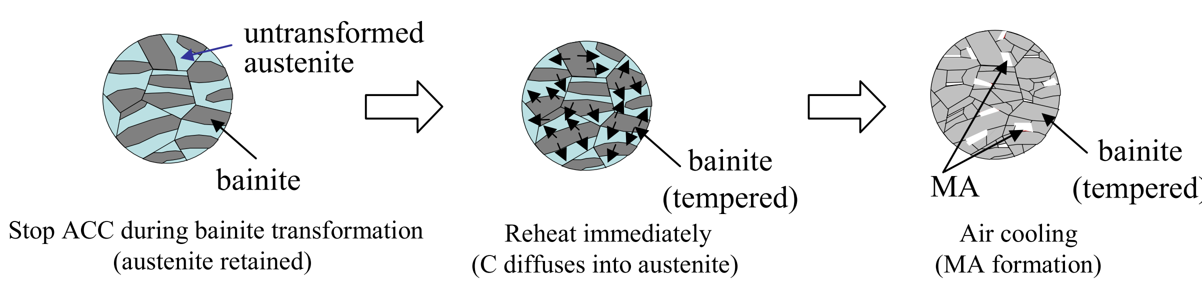


Figure 8. Schematic illustration of new microstructural controlling process to obtain bainite with dispersed MA by using heat treatment online process.

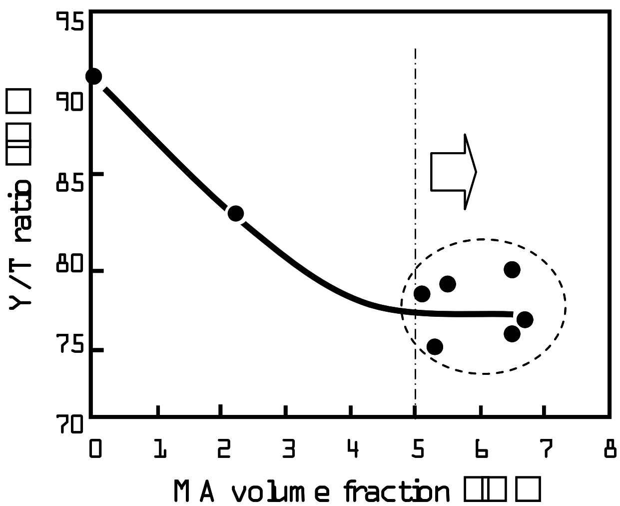


Figure 9. Effect of volume fraction of MA on Y/T ratio of bainitic steel.

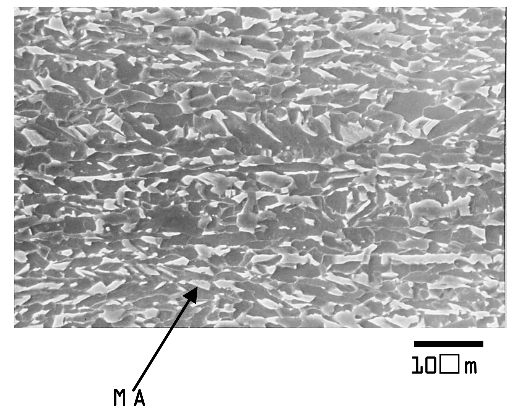


Figure 10. Microstructure of high deformability linepipe with bainitic microstructure containing MA.

Based on the above considerations on controlling microstructure to contain MA, trial production of grade X80 linepipe was conducted. Continuously cast steel slabs were controlled-rolled to plates of 15.6 and 17.5mm in thickness, the plates were accelerated cooled, and then on-line heating process (HOP) was applied in order to promote formation of MA. Microstructure of the plate is shown in Fig. 10. Bainite with fine dispersed MA can be observed. The volume fraction of MA was above 7%. This value is sufficient to lower the Y/T ratio of the steel.

Trial production of an X80 linepipe was carried out by UOE process. Table 2 shows dimensional and mechanical properties of the trial grade X80 linepipes. Both pipes have round-house type stress-strain curve, and Y/T ratios in the longitudinal direction were lower than 80%.

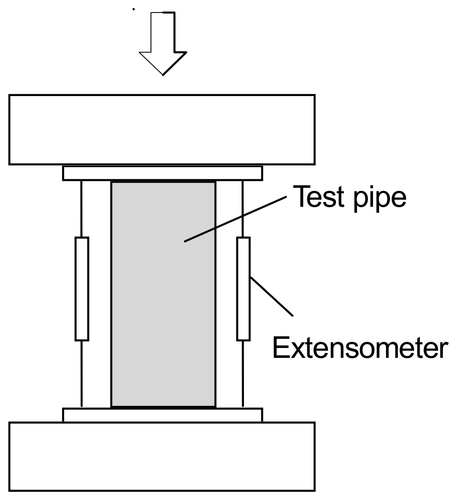
Table 2. Mechanical properties of the high deformability linepipes with bainite-MA microstructure.

Grade	Dimention			Tensile properties [1)]				Impact properties	
	OD (mm)	WT (mm)	D/T	YS (MPa)	TS (MPa)	Y/T (%)	n	vE_{-10} (J)	vTrs (^oC)
X80	762.0	15.6	49	532	702	76	0.12	271	-98
	1016.0	17.5	58	581	734	79	0.14	264	-105

[1)] Longitudinal direction

Uni-axial BucklingTest of the Trial Pipes

Full scale buckling tests were carried out for the newly developed pipes. Schematic illustration for the uni-axial buckling test is shown in Figure 11. Buckling strain, defined by the strain when the load reaches the maximum point, was plotted as a function of D/t, comparing with the results of conventional pipes in Figure 12. All developed pipes have a higher buckling strain than conventional pipes because of Round-house type stress-strain curve and higher n-value.



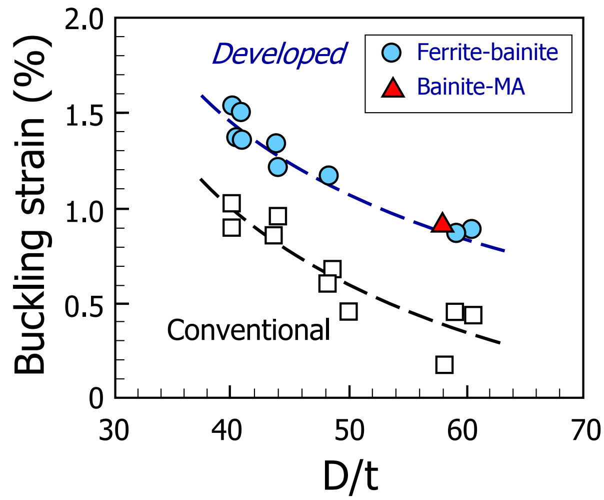


Figure 11. Uni-axial compression test procedure

Figure 12. Relation between buckling strain and diameter to thickness ration.

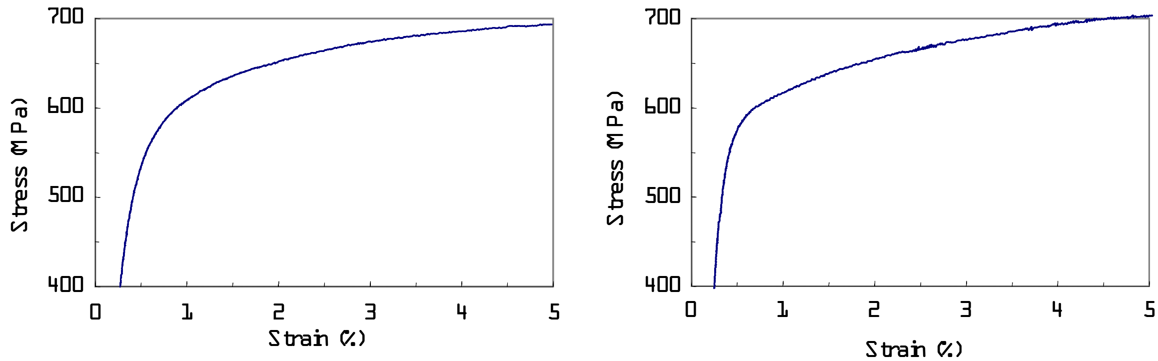
Strain Aging Behavior by Thermal Coating

Strain aging is caused by the interaction of dislocation and diffusible carbon atoms. Dislocations induced by plastic deformation are immobilized by carbon atoms activated by heating, resulting in the increase of yield stress. It was reported that the yield strength and Y/T ratio of UOE pipes are increased by thermal coating [12]. It is considered that dislocations are induced by phase transformation during accelerated cooling processing and diffusible carbon may remain after accelerated cooling of the plate, and this may be one of the reasons for strain aging by pipe coating.

The newly developed metallurgical controlling process described above can be a process that minimizes the strain aging effect. On-line heating process is applied subsequently to the accelerated cooling process in this newly developed method. During the on-line heating process, recovery of dislocation is promoted, and diffusible carbon is reduced as a result of formation of carbides. Recovery of dislocations leads to softening of bainite phase, however, the most important feature of this new process is the formation of MA, and this enables the balance of high strength and high deformability, as well as resistance to strain aging.

In order to investigate the effect of thermal coating on stress-strain behavior of the developed X80 linepipe, actual external FBE coating was carried out. Three induction coils were used in order to apply the thermal treatment. The highest temperature of the pipe outer surface was 232 deg.C. After coating, the coated pipe was water-cooled.

Figure 13 shows longitudinal stress-strain curves by full thickness strip specimens before (as UOE) and after the thermal coating. Round-house type stress-strain curves can be maintained even after thermal coating. A slight increase in longitudinal yield strength occurred but the increase was minimized up to 30MPa even after pipe coating at 232°C. Longitudinal Y/T ratio after coating was 83%. Although further investigation is necessary to assure the anti-strain aging property and high deformability after coating, this new metallurgical controlling process can be one of the solutions to suppress yield stress increase after coating and to balance high strength and high deformability of pipes.



(a) (b)

Figure 13. Longitudinal stress-strain curves of developed linepipe measured by full thickness strip specimens (a) before and, (b) after the thermal coating.

Conclusions

1) The effect of the stress-strain relationship was investigated by axial compression testing of small-scale pipes, and it was shown that the pipes with round-house type stress-strain curves and higher n-value provide a higher resistance to buckling.
2) The effect of microstructural characteristics of stress-strain behavior of dual-phase steels was investigated by theoretical modeling based on inclusion theory and the finite element unit cell model.
3) Based on the analytical study on the optimum microstructure for obtaining round-house type stress-strain curve and higher n-value, high deformability linepipes with two different types of microstructure, ferrite-bainite microstructure and bainitic microstructure containing dispersed fine MA, were developed. Resistance to buckling of developed pipes was verified by full scale uni-axial compression test.
4) Strain-age hardening behavior of developed pipe was investigated by applying external FBE coating. It was demonstrated that an increase in yield strength is minimized by applying newly developed metallurgical controlling processing. The developed grade X80 linepipe with a microstructure of tempered bainite with MA shows sufficient tensile properties for buckling resistance not only as UOE, but also after 232º C coating simulation.

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