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Microstructural Aspect of Deformability of High Strength Linepipe Steels

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Abstract

Small and large scale buckling tests using the steel pipes with various tensile properties revealed that there is a strong effect of stress-strain curve on buckling behavior in axial compression. Especially, buckling strain was improved by increasing strain hardening exponent in the longitudinal direction. Strain hardening exponent can be controlled by controlling microstructure of ferrite-bainite two-phase steels. Micromechanical model for simulating the deformation behavior of two-phase steel was developed by applying Voronoi type finite element unit cell. Microscopic deformation behavior of two-phase steels and the effect of microstructural characteristics, such as volume fraction and aspect ratio of the second phase, were investigated with respect to the stress-strain relation of two-phase steels. Finally, high strength linepipes with higher buckling resistance were developed based on the analytical investigation.

Key words: linepipe, buckling, deformability, microstructure, cell model

1. INTRODUCTION

Strength grade of linepipe steels have been increasing in order to fulfill the recent requirement for total cost reduction of pipeline systems[1]. On the other hand, higher deformability is required for the linepipes installed on the seismic region or permafrost ground in order to prevent plastic buckling by large ground movement. It is well understood that earth quake resistance property of the steel constructions is improved by lowering Y/T ratio (yield ratio) of the steel. Y/T ratio is strongly affected by microstructure of the steel[2], however, it becomes difficult to balance lower Y/T ratio and higher strength.

In this study, uniaxial compression tests were conducted using the pipes with various tensile properties in order to investigate the effect of material properties on buckling behavior. Then, optimum microstructural characteristics were investigated by analytical method such as the finite element unit cell models which can simulate microscopic behavior of the two-phase steels and estimate the mechanical properties. Based on the analytical investigations, high strength linepipes with superior deformability, which means high strain hardenability to prevent buckling, were developed and buckling resistant property was demonstrated by full scale buckling test.

2. BUCKLING BEHAVIOR OF STEEL PIPES

2.1 Experimental procedures

Small scale steel pipes were manufactured by different steel plates with tensile strength of 500-780 MPa, which varied in microstructure and tensile properties. All pipes had the same outer diameter(D), but wall thickness (t) were changed from 1.5mm to 5.0mm, accordingly, diameter to thickness ratio(D/t) was changed from 33 to 67. Longitudinal tensile properties were measured on the test

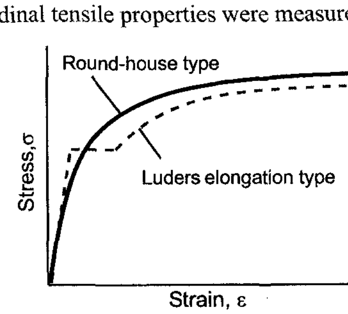

Fig. 1 Stress-strain curves.

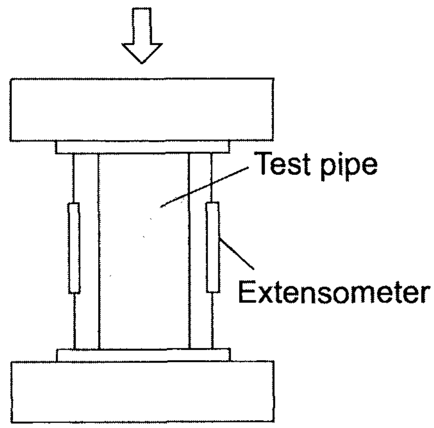

Fig. 2 Axial compression test procedure.

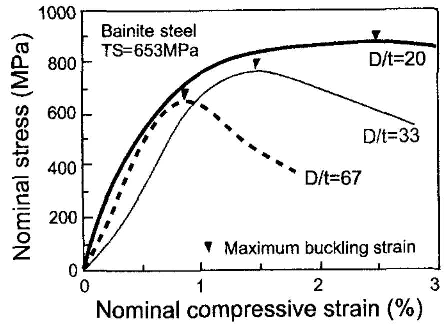

Fig. 3 Nominal stress-nominal compressive strain curves.

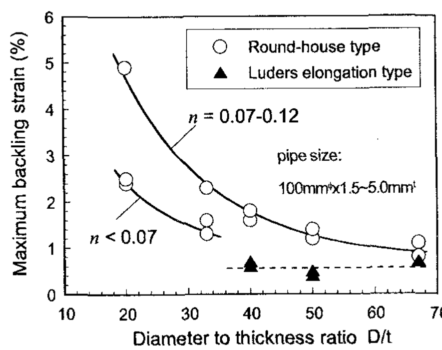

Fig. 4 Relation between maximum buckling strain and D/t of the small scale pipes.

pipes and stress-strain curves were categorized into "Luders elongation type" and "Round-house type" as shown in Fig. 1. Strain hardening exponent (n-value) was evaluated as following equations,

$$\sigma = A\varepsilon^n \quad (1)$$

where, σ, ε, n and A are true stress, true strain, n-value and constant, respectively. The n-value was evaluated for the steel with Round-house type stress-strain curve in the strain range from 1% to 4%. The small scale pipe specimens were subjected to the uniaxial compression test as shown in Fig. 2.

2.2 Results of buckling test

As an example, the nominal compressive stress-nominal compressive strain curves for the pipe with tensile strength of 653MPa and bainitic microstructure were shown in Fig. 3. Local buckling was occurred just around the maximum stress, and the strain that showed maximum stress was defined as the maximum buckling strain. The maximum buckling strains for all the pipes tested were compared as a function of D/t in Fig. 4. Buckling occured around yield strain for the pipes with Luders elongation type stress-strain curves. On the other hand, the maximum buckling strain decreases with increasing D/t ratio for the pipes with Round-house type stress-strain curve. And, pipes with higher n-value showed higher buckling strain. In addition, the steels with ferrite-bainite microstructure showed higher n-value than other microstructure.

It is considered that buckling initiates because of inhomogeneity of material property or pipe geometry, such as the local portion with lower strength or thinner wall thickness. If the material has higher n-value, locally strained region is strengthened by strain hardening and buckling can be delayed. However, abrupt strain increase may occur at the yield stress for the pipes with Luders elongation, resulting in buckling of the pipe in the lower strain level.

As a results of the buckling test of the small scale pipes, suggestion for material properties for the pipes with buckling resistance was induced. That is, the material with Round-house type stress-strain curve and higher n-value is preferable. And, there is a large possibility of obtaining those property by controlling ferrite-bainite microstructure of steels.

3. ANALYTICAL STUDY FOR OPTIMIZING MICROSTRUCTURE

3.1 Voronoi tessellation of BCC lattice (V-BCC) model

In order to investigate the effect of microstructural characteristics on the stress-strain curves, finite element unit cell model was applied. Socrate and Boyce[3] and Ishikawa et al.[4] proposed micromechanical model based on a staggered array of particles. In this model, a truncated octahedron, the Voronoi cell on the BCC lattice is used as a space filling polyhedron as shown in Fig. 5(a). The second phase particles are arranged on a regular BCC lattice. 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 particle. Fig. 5(b) shows two adjacent axisymmetric Voronoi

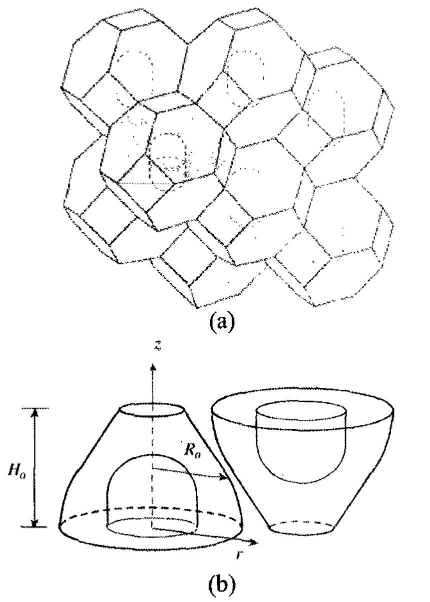

Fig. 5 The V-BCC model: (a) three dimensional array of Voronoi tessellation of the BCC lattice, (b) two adjacent axisymmetric V-BCC cells.

cells. Hight of the unit cell was set as $H_0=1$ in the analysis. Geometric compatibility of the deformation in the two antisymmetric cells requires the constraint of the radial and axial displacement of outer boundary as follows,

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

$$U_z(\xi)+U_z(1-\xi)=2U_z|_{0.5} \quad (3)$$

where, $U_r(\xi)$ and $U_z(\xi)$ is the radial and axial displacement of the outer boundary at $z=\xi$. These boundary conditions are one of the significant feature of the V-BCC model, which is less constrained than conventional models and large plastic flow can be allowed in the matrix material. For the detailed explanation for the V-BCC model, refer to Socrate and Boyce[3].

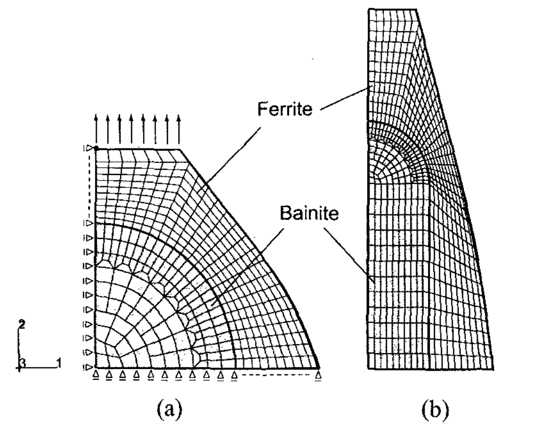

Fig. 6 Finite element meshes for ferrite-bainite steels: (a) aspect ratio of bainite phase, *Ra*=1.0, (b) *Ra*=4.0

3.2 Stress-strain behavior of ferrite-bainite steels

Ferrite-bainite microstructure was selected for the analysis because 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. Fig. 6 shows examples of the finite element meshes for 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. Bainite volume fraction and bainite aspect ratio were changed in order to investigate the effect of microstructural characteristics.

Fig. 7 shows nominal stress-nominal strain curves of ferrite-bainite steel with different bainite volume fraction obtained by the V-BCC model. Bainite aspect ratio was $R_a=2.0$. The stress-strain curves for the bainite and ferrite phases were also plotted in Fig. 7. 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 bainite

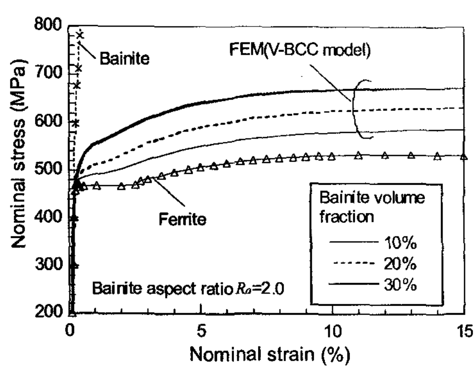

Fig. 7 Effect of bainite volume fraction on stress-strain curves for the ferrite-bainite steels with bainite aspect ratio of $R_a=2.0$

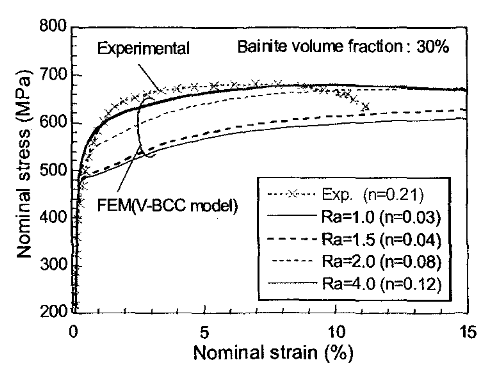

Fig. 8 Effect of bainite aspect ratio on stress-strain curves for the ferrite-bainite steels with bainite volume fraction of 30%

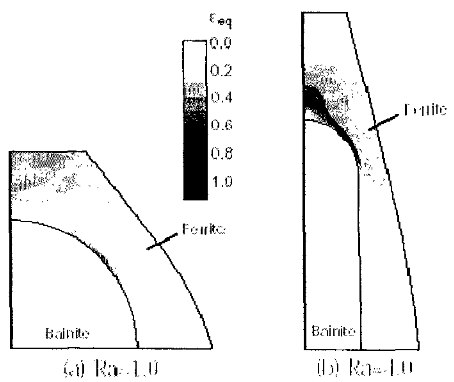

Fig. 9 Contour plots of equivalent plastic strain at nominal strain of 2.0%.

volume fraction of 30%. Fig. 8 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 R_a=4.0. Local distribution of equivalent strain inside each phase in the case of R_a=1.0 and 4.0 were shown in Fig. 9. Large strain concentration is seen in the ferrite phase around the top of the elongated bainite for the ferrite-bainite with R_a=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, and this can be the reason for higher stress after yielding and higher *n*-value. Therefore, it was suggested that ferrite-bainite steel with elongated bainite showed Round-house type stress-strain curve with higher *n*-value.

4. DEVELOPMENT OF HIGH STRENGTH LINPIPES WITH SUPERIOR DEFORMABILITY

Based on the above considerations on controlling microstructure, high strength linepipes were developed, aiming to have higher deformability for buckling resistance by controlling stress-strain curves to Round-house type with higher *n*-value. Table 1 shows examples of API Grade X65 -X80 linepipes developed. All steels have ferrite-bainite microstructure which was obtained by applying controlled rolling followed by accelerated cooling process. Microstructural characteristics were carefully controlled by controlling the chemical compositions and plate manufacturing parameters, resulting in balancing higher strength and higher n-value same as lower Y/T ratio in the longitudinal direction of the pipe.

Full-scale buckling tests were carried out for the developed pipes by the same procedure as described in Fig. 2. Maximum buckling strain was plotted as a function of

Table 1 Linepipes developed for buckling resistance

Grade	Dimension			Tensile properties [1]				Impact properties	
	OD (mm)	WT (mm)	D/T	YS (MPa)	TS (MPa)	Y/T (%)	n	vE$_{-10}$ (J)	vTrs (°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

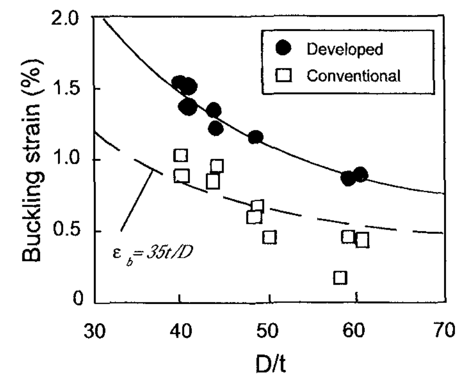

Fig. 10 Relation between buckling strain and diameter to thickness ratio in full scale buckling test.

diameter to thickness ratio, D/t, comparing with the results of conventional pipes. All developed pipes have higher buckling strain than conventional pipes because of Round-house type stress-strain curve and higher *n*-value. It can be said that large amount of experimentation for searching appropriate microstructure was able to be eliminated by applying analytical approach for optimizing microstructure of the steel.

5. CONCLUSIONS

Effect of microstructural characteristics of stress-strain behavior of ferrite-bainite steel was investigated by finite element unit cell model. Based on the analytical study on the optimum microstructure for obtaining Round-house type stress-strain curve and higher *n*-value, API grade X65 to X100 high strength linepipe for buckling resistance were developed. It was proved that developed pipes have higher buckling strain than conventional pipes by full-scale buckling tests.

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