Development of High Strength Linepipes with Excellent Deformability

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ABSTRACT

Extensive studies to develop high strength linepipes with higher deformability have been conducted. As two-phase microstructure consisted of harder and softer phases are essential to obtain larger deformability, the optimum microstructural characteristics in terms of deformability were investigated by analytical methods that can simulate microscopic behavior of the two-phase steels. The harder and higher volume the harder phases becomes, the larger the work hardenability of two-phase steels becomes. Based on the analytical results, two types of high deformability linepipes which have ferrite-bainite and bainite–martensite (MA) microstructures have been developed. The ferrite-bainite type material has been produced by applying ordinary TMCP made up with controlled rolling (CR) and accelerated cooling (AcC). In the accelerated cooling stage, lowering cooling finishing temperature has significant effect of increasing work hardenability. The material with bainite-MA microstructure has been produced by applying a new type of TMCP composed with CR, AcC and On-line tempering. Those materials show sufficient strength and deformability for high strength linepipes being able to be used in long distance pipelines crossing the area where large movements of ground could be expected.

KEYWORDS
High strength linepipes, Deformability, Work hardenability, Two phase microstructure, Ferrite-bainite, Bainite–martensite (MA) microstructures, TMCP, Accelerated Cooling, On-line tempering.

INTRODUCTION

Recent studies [1] indicate the significant economical advantages of using higher grade linepipes in constructing long distance pipelines. Those advantages can be brought by increasing transportation efficiency of pipelines and reducing material costs. The thinner wall materials bring the lower total tonnage of material itself and consumables for girth welding. On the other hand, pipelines laid in places where larger strains can be expected by ground movements have been designed according with a new concept so called “strain base design”[2]. According to the concept, higher resistance of linepipes against the larger compressive and tensile strains is required. Stringent control of yield strength range of the pipes is also important to keep over-matching in 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 work hardenability (lowering yield to tensile ratio) of the steel. The work hadenability is strongly affected by microstructure of the steel [3]. As two-phase microstructure consisted of harder and softer phases are essential to obtain larger work hardenabilty and the resulting higher deformability, the optimum microstructural characteristics for higher deformability were investigated by analytical methods which can simulate microscopic behavior of the two-phase steels [5].
According with the analysis results, two types of high deformability linepipes which have ferrite-bainite and bainite–martensite (MA) two-phase microstructure have been developed. Those could saw higher resistance to buckling and fractures against large strain induced by ground movements, such as liquefaction and fault. Microstructural controlling concept studied by FEA, evolution of microstructure in each TMCP stages (such as CR, AcC and On-line tempering) and mechanical properties of the developed linepies are introduced.

The effects of thermal cycle of coating on the mechanical properties were also investigated. The threshold of coating temperatures for maintaining the deformability and the strength matching of girth welds of the linepipes developed are also presented

1. ANALYTICAL STUDIES FOR OPTIMIZATION OF MICROSTRUCTURE OF TWO PHASE STEELS IN TERMS OF DEFORAMBILITY

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

In order to investigate the effect of microstructural characteristics on deformability (work hardenability) of two-phase steels, theoretical model so called "Micromechanics" was applied [6]. This continuum model is based on the Eshelby's inclusion theory [7], the Mori-Tanaka's mean field concept [8] 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 relation of each constituent phase. In order to calculate the macroscopic stress-strain curves of DP steels, each composite should be given in form of a numerical equation. The main stress-strain equation used in the continuum plastic theory is the following Swift's equation:

$$\sigma_{\mathrm{i}} = a_{\mathrm{i}}\,(b_{\mathrm{i}} + \varepsilon_{\mathrm{pi}})^{n\mathrm{i}} \qquad (1)$$

where i means ith 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 Fig. 1.

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

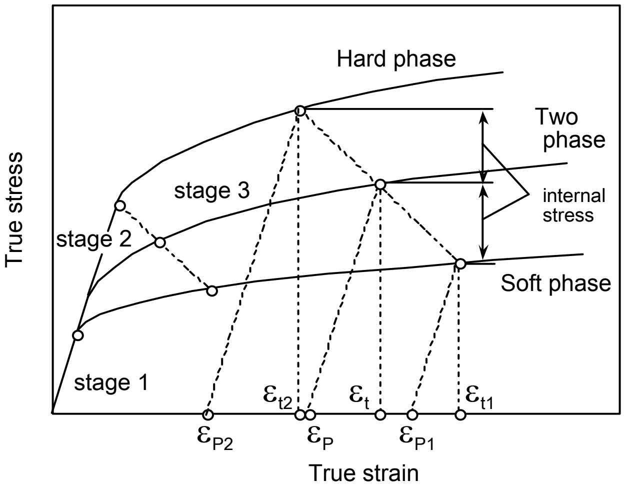

Fig . 1 Stress-strain curves of two phase material, hard and soft phases showing the 3 stages of the model.

Using the before mentioned model, the effect of strength difference between hard phase and soft phase and the effect of volume fraction of soft phase on work hardening exponent (n in eq.1) as a parameter for deformability of the steels were investigated. Three types of two-phase steels were used for the analysis. In all the cases, ferrite was set as the soft phase, and as hard phase, pearlite, bainite and martensite were selected. Stress-strain curves for each constituent phase were experimentally measured and expressed by eq. (1). Analysis results on n-value in the stage II was plotted as a function. tensile strength difference in Fig. 2. n-value increases with increasing strength difference and with increasing volume fraction of hard phase. Ferrite-bainite steel showed higher n-value than ferrite-pearlite steel, while ferrite-martensite steel has highest n-value. Higher n-value such as more than 0.1 can be obtained for the ferrite-bainite steel when bainite fraction is more than 30%. However, 10% of the hard phase is enough for ferrite-martensite steel to obtain same n-value as ferrite-30%bainite steel.

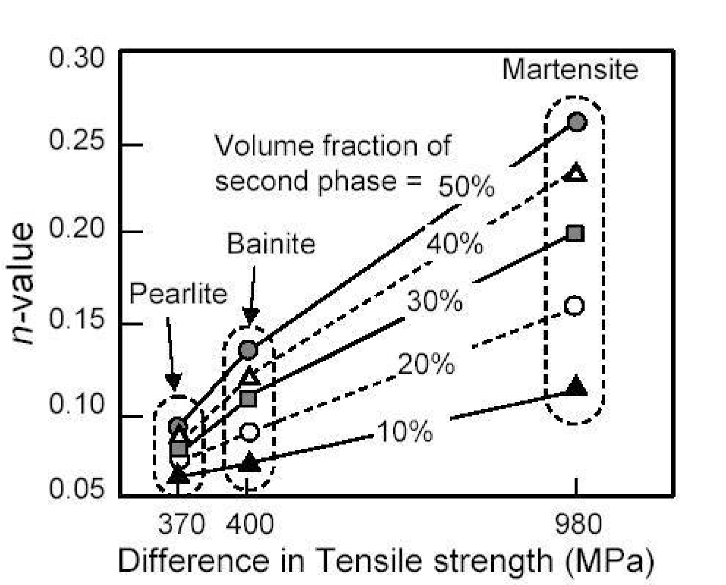

Fig . 2 Effect of difference in strength on work hardening behavior of the two-phase steels.

Predicting Stress-Strain Behavior of Ferrite-Bainite Steels by FEA

Micromechanics is a quite useful tool for estimating stress-strain behavior of two-phase steel. However, it is based on the inclusion theory and hard second phase is treated as a spherical particle. Therefore, close examination on the effect of morphology of the second phase was conducted using finite element unit cell model. Socrate and Boyce [9] and Ishikawa et al [10] proposed micro-mechanical model based on a staggered array of particles.

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.3 shows examples of the finite element meshes for ferrite-bainite microstructure with the bainite volume fraction of 30% and the 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. 4 shows nominal stress-nominal strain curves of ferrite-bainite steel with different bainite volume fraction obtained by V-BCC model. Bainite aspect ratio, Ra, was 2.0. The stress-strain curves for the bainite and ferrite phases were also plotted in Fig. 4. Ferrite phase itself has a Luders elongation, however, the Luders elongation became small as bainite volume fraction increased. And round-house type stress-strain curve was obtained by the bainite volume fraction of 30%.

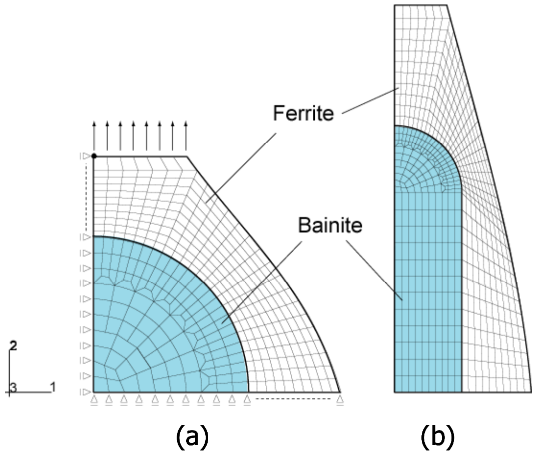

Fig.3 Examples of the finite element meshes for ferrite-bainite microstructure with the bainite volume fraction of 30% and bainite aspect ratio of 1.0 and 4.0.

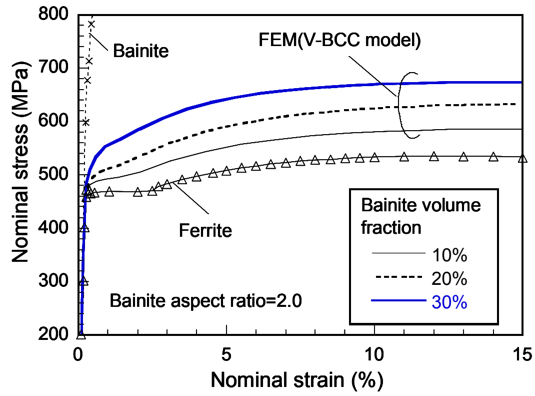

Fig. 4 shows nominal stress-nominal strain curves of ferrite-bainite steel with different bainite volume fraction

Fig. 5 shows the maximum strains in the softer phase as a function of nominal strain. The maximum strain becomes larger with increasing the bainite volume fraction. As the minimum strains in the softer phase does not show any significant difference with changing volume fraction of bainite, larger strain distribution in the softer phase is one possible reason for eliminating Luders elongation of higher bainite volume fraction materials.

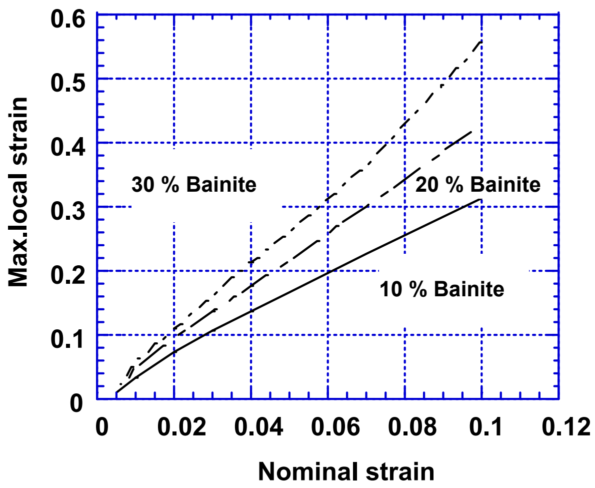

Fig. 5 The maximum strains in the softer phase as a function of nominal strain.

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. 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 higher strain causes deformation of the harder bainite phases even in lower nominal strain ranges, and this can be the reason for higher stress after yielding and higher n-value.

As the ferrite-bainite steel with larger volume and elongated bainite can give round-house type stress-strain curve with higher n-value, this is the microstructure targeted to achieve high deformability .

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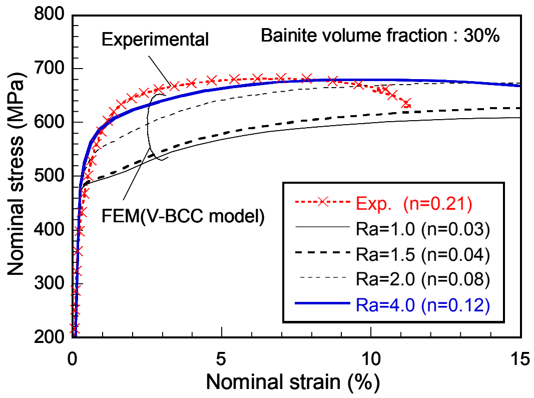

Fig. 6 The effect of bainite aspect ratio on stress-strain curves

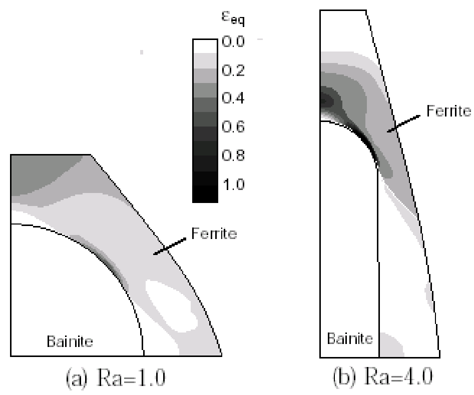

Fig. 7 Local distribution of equivalent strain inside each phase in the case of Ra=1.0 and 4.0

2. DEVELOPEMENT OF HIGH STRENGTH LINEPIPES WITH SUPERIOR DEFORMABILITY

According with the analysis results, two types of high deformability linepipes which have ferrite-bainite and bainite–martensite (MA) two-phase microstructure have been developed.
Plate manufacturing for the ferrite-bainite steel is ordinal TMCP with precise temperature control in AcC stage. Because strict microstrucural control is need to achieve high deformability, this precise temperature control is essential to produce the high deformable materials. To meet the requirement, *Super*-OLAC system has been applied. The system main features are extremely high and uniform cooling ability. Temperature scattering in a plate after AcC is much smaller than that of the old systems. And this brings higher strength plates with lean materials easily and uniformity of the plates in mechanical properties and shape (Fig. 8) [11].
Plate manufacturing process for Ferrite-MA steel is new TMCP composed with CR, AcC and on-line heating. Because of applying on-line heating [12], the later one shows stable mechanical properties even being suffered from thermal cycles after pipe forming, such as higher temperature coatings.

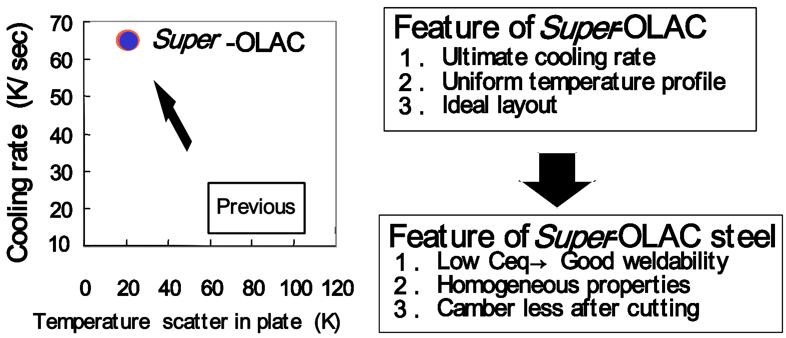

Fig. 8 *Super*-OLAC system main features

3. HIGH DEFORMABILITY LINEPIPES WITH FERRITE-BAINITE MICROSTRUCTURE MANUFACTURED BY ACC PROCESS

Metallurgy for Producing ferrite-bainite Two-Phase Steels by AcC Process

To produce the ferite-bainite type microstructure by using ordinal TMCP, optimization studies for

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AcC parameters were conducted. The purposes of the studies are to clear the effect of AcC starting temperature on volume of bainite and the effect of AcC finishing temperature on morphology of bainite. Fig. 9 shows the effect of AcC starting temperature on microstructural changes of a AcCed steel. In the case of the AcC temperature higher than transformation starting temperature, bainite single phase microstructure can be obtained (a of Fig 9). On the other hand, when the temperature is less than the transformation starting temperature ferrite-bainite type two-phase microstructure targeted can be obtained.

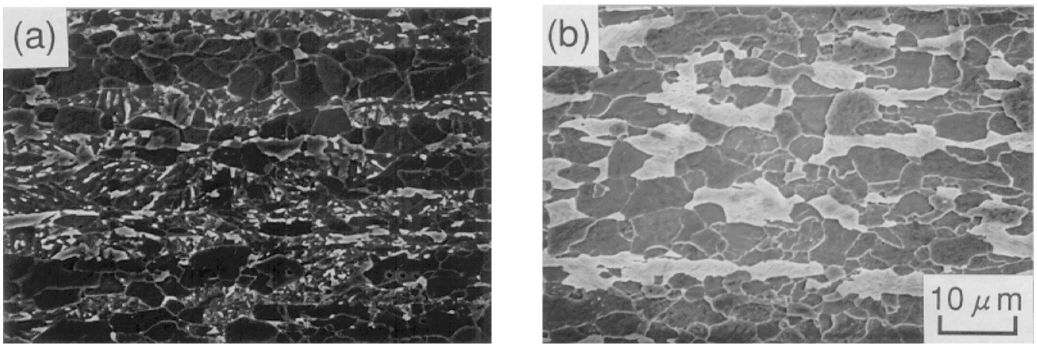

Fig. 9 shows the effect of AcC starting temperature on microstructural changes of a AcCed steel.

To understand morphology of the second phase in the bainite phase is also important to control strength (hardness) of the harder phase. The effect of accelerated cooling finishing temperature on the bainite microstructure was examined. SEM microphotographs of the steels with different cooling finishing temperature were shown in Fig.9. Two stages electrical etching was conducted on the specimens in Fig.9, showing only M-A as second phase. Relation between volume fraction of second phase and cooling finishing temperature is shown Fig.10. The main second phase is cementite if the cooling finishing temperature is above 400°C, and M-A is produced mainly under 400°C. As is mentioned in the previous section, the harder second phase brings higher work hardenability of two-phase steels. In this sense, it is obvious that lower AcC finishing temperature have significant advantage.

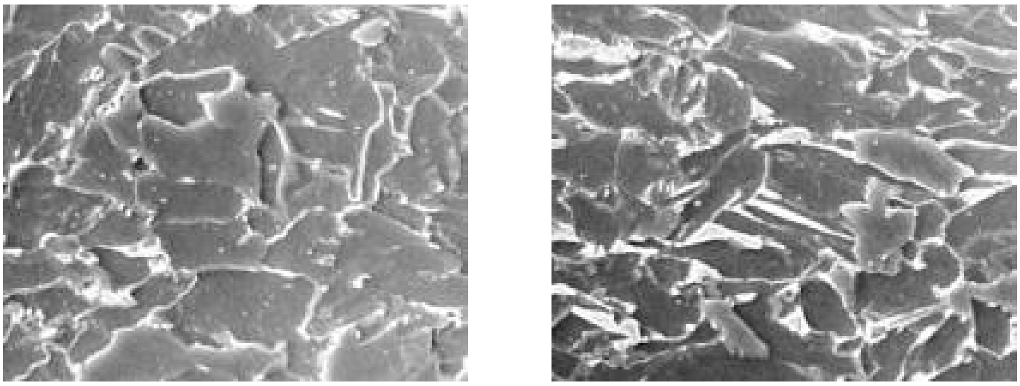

Fig.9 SEM micrographs of the steels with various cooling finishing temperature, (a) 560°C, (b) 305°C

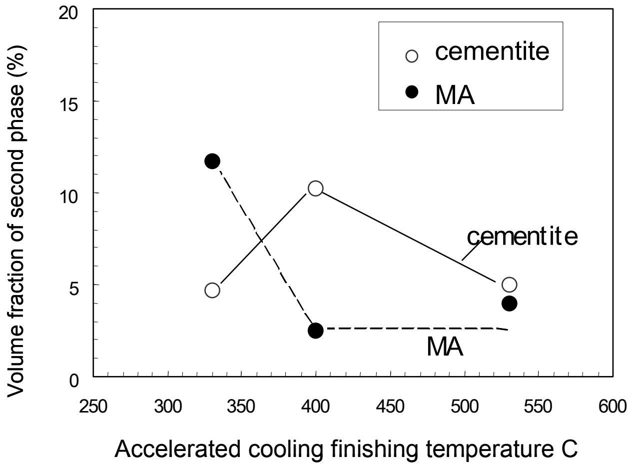

Fig.10 Relation between volume fraction of second phase and cooling finishing temperature

Two-Phase steel Linepipes Developed

Based on the above considerations on controlling microstructure, high strength linepipes were developed, aiming to have 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 ferrite-bainite microstructure which was obtained by applying controlled rolling followed by accelerated cooling process. Fig.11 shows an example of microstructure of the developed high deformability linepipe. Carefully controlled microstructure results in balancing higher strength and higher n-value same as lower Y/T ratio in the longitudinal direction of the pipe.

Table 1 shows examples of API Grade X65-X100 linepipes developed

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)] Lingitudinal direction

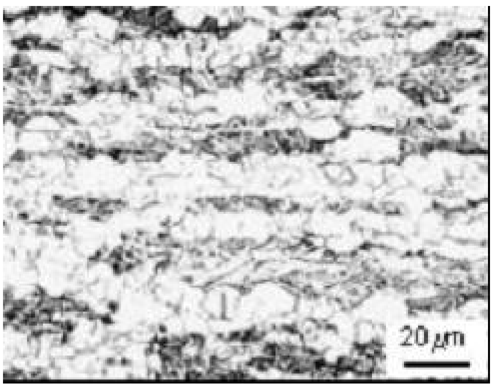

Fig.11 shows an example of microstructure of the developed high deformability linepipe

4. HIGH DEFORMABILITY LINEPIPES WITH BAINITIC MICROSTRUCTURE WITH CONTAINING DISPERSED FINE M-A CONSTITUENTS

Metallurgy for Producing Two-Phase Steels by New TMCP

As discussed in the previous section, two-phase microstructure which containing harder second phase, such as martensite, shows higher n-value even with relatively small amount of hard phase. In order to obtain dual phase microstructure containing martensite-austenite constituents (MA), new microstructure controlling process was developed, by applying heating process subsequently after accelerated cooling. Fig.12 shows the schematic illustration of the new microstructure controlling process. This process consists of three stages. Accelerated cooling (AcC) is stopped at above the bainite transformation finishing temperature, where untransformed austenite remains. It is known that bainite transformation is incomplete transformation, and transformation stasis, which transformation stops for some moment is observed [13]. Fig.13 shows the results of dilatometric experiment for bainite transformation behavior after AcC. Fig.14 shows the continuous cooling diagram of the steel used. Bainite transformation starts at approximately 570°C in the cooling rate of 30°C/s. The temperatures of 500 and 550°C are in the middle of the temperature range of bainite transformation. As shown in Fig.9, transformation stasis was occurred during isothermal heat treatment at 500°C and 550 °C after AcC. It is suggested that untransformed austenite can be obtained when AcC halt in this temperature range.

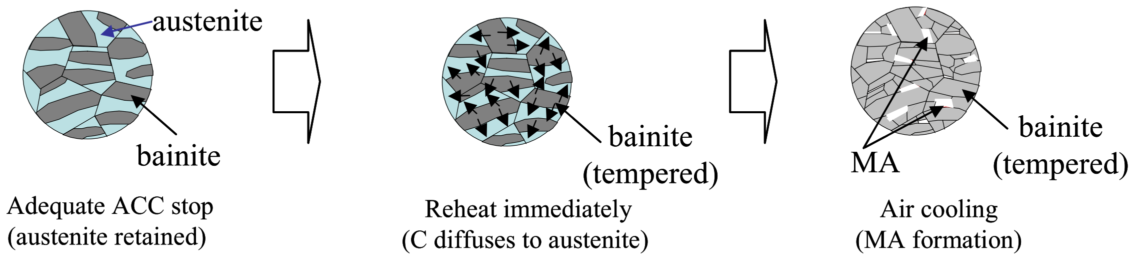

Fig. 12 The schematic illustration of the new microstructure controlling process

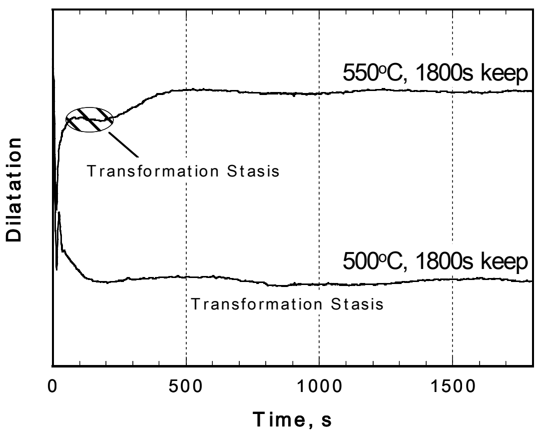

Fig.13 Bainite transformation behavior during after accelerated cooling

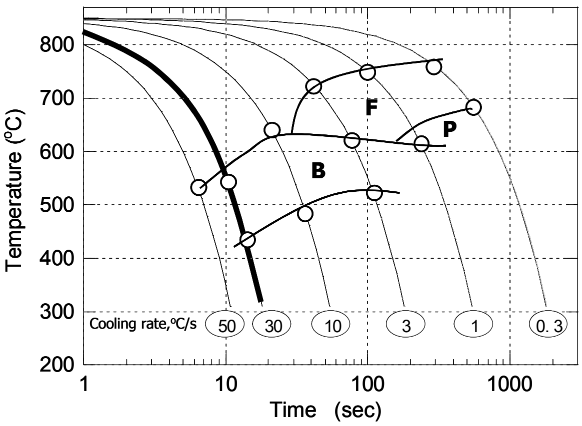

Fig.14 Continuous cooling diagram of the steel used

Immediately after AcC, reheating process is employed by using the on-line heating device. During the heating, carbon in bainite diffuses into the before mentioned retained austenite. After the heating, the C concentration in the austenite becomes higher than that of austenite immediately after AcC halting stage. This austenite can transform into MA even during slower cooling such as, air cooling,

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because of the existence of highly concentrated carbon in it. During the heating, ferrite transformation from some part of austenite also occurs. At the same time, row precipitation of nano-meter sized carbides that bring extremely high strength forms at the austenite/ferrite interface (Fig.15).
Advantage of this new process is to be able to control second harder phase and to utilize precipitation strengthening that cannot obtain in conventional TMCP.

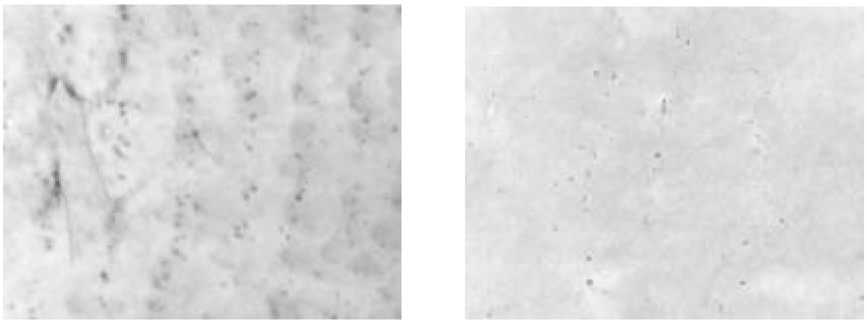

Fig.15 TEM micrographs of the steels with (a) and (b) new TMCP process

Two-Phase steel Linepipes Developed

Based on the those considerations on controlling microstructure to contain MA, trial production of an X80 linepipes was carried out by UOE process. A continuously cast steel slabs were controlled-rolled to plates of 15.6 and 17.5mm in thickness. Table 2 shows dimension and mechanical properties of the trial grade X80 linepipes. 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. Both pipes have round-house type stress-strain curve, and Y/T ratio in the longitudinal direction were lower than 80%. Uni-axial buckling test on the pipes developed were carried out. Those tests revealed that the pipes have 1.5 to 2 times larger the buckling strains compared with those of ordinaly high strength linepipes (Fig.16). Thus, those materials show sufficient strength and deformability for high strength linepipes being able to be used in long distance pipelines.

Table 2 Tensile properties of X80 linepipe newly developed.

Grade	Dimention			Tensile properties [1]				Impact properties	
	OD (mm)	WT (mm)	D/T	YS (MPa)	TS (MPa)	Y/T (%)	n	vE_{-10} (J)	vTrs (°C)
X80	762	15.6	49	532	702	76	0.12	271	-98
	1016	17.5	58	581	734	79	0.14	264	-105

[1] Longitudinal direction

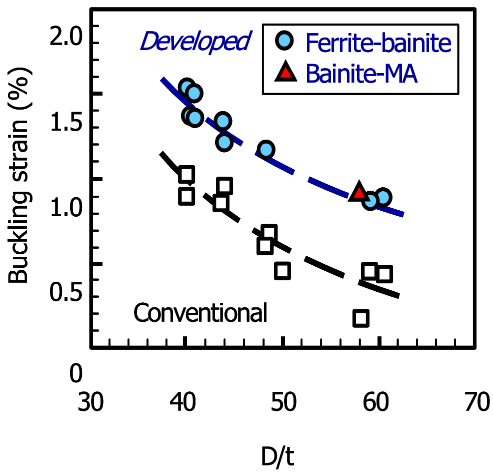

Fig. 16 Relationship between buckling strain and diameter to thickness ratio in full scale buckling test.

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 increase of yield stress. It was reported that yield strength and Y/T ratio of UOE pipe are increased by thermal coating. It is considered that dislocations are induced by phase transformation during accelerated cooling process 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 in Fig. 13 can be a process that minimize the strain aging effect. On-line heating process is applied subsequently after accelerated process in this newly developed process. 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 to balance 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 developed grade 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 pipe outer surface was 232 deg.C. After coating, the coated pipe was water-cooled.

Fig.17 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. Slight increase in longitudinal yield strength is occurred but the increase was minimized up to 30MPa even after the pipe coating at 232 deg.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.

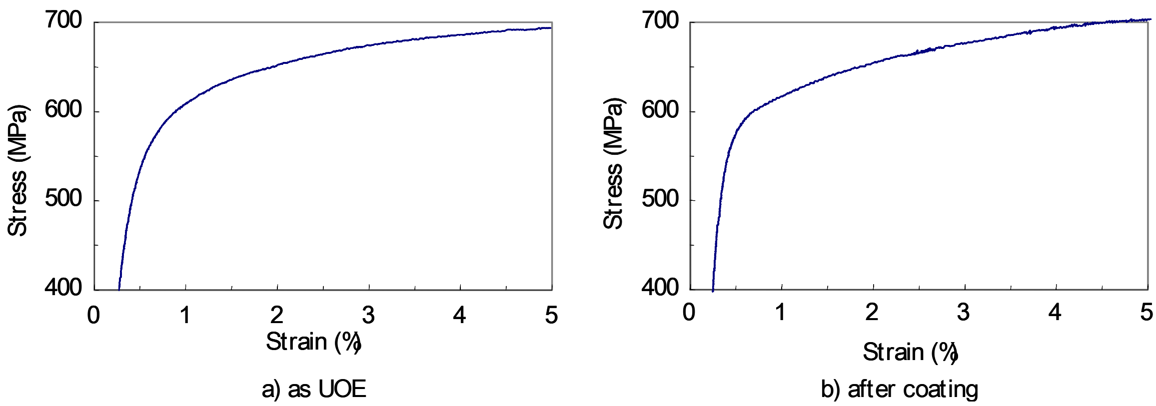

Fig.17 longitudinal stress-strain curves by full thickness strip specimens before and after the thermal coating

4. CONCLUSIONS

1) Effect of microstructural characteristics of stress-strain behavior of dual-phase steels was investigated by theoretical model based on inclusion theory and finite element unit cell model. As the ferrite-bainite steel with larger volume and elongated bainite can give round-house type stress-strain curve with higher n-value, this is the microstructure targeted to achieve high deformability

2) 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. Higher resistance to buckling of developed pipes was verified by full scale uni-axial compression test. Those materials show sufficient strength and deformability for high strength linepipes being able to be used in long distance pipelines crossing the area where large movements of ground could be expected.

4) Strain-aged hardening behavior of developed pipe was investigated by applying external FBE coating. It was demonstrated that increase in yield strength is minimized by applying the newly

developed process. Developed grade X80 linepipe that microstructure is tempered bainite with MA shows sufficient tensile properties for buckling resistance not only as UOE, but also after 232 deg.C coating.

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