High Performance UOE Linepipes†

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Abstract:

Recent construction location of natural gas pipelines is expanding toward remote regions and regions under severe environmental conditions. This requires linepipe materials to have higher strength with properties suitable for the environment, such as high deformability or sour gas resistance. JFE Steel has developed series of high strength UOE linepipes with various excellent properties by applying cutting edge processing technologies: "Super-OLAC," on-line accelerated cooling, and "HOP," heat-treatment on-line process by induction heating. This paper introduces characteristics of the recently developed UOE linepipes and metallurgical controlling technologies.

1. Introduction

Recently, the demand for natural gas has been expanding as a clean energy resource with a little exhaust of CO_2. Japan is importing the natural gas as liquefied natural gas (LNG), while pipeline is used for transportation of natural gas from gas field to consumption region or LNG base. As the exploration of natural gas field is expanding toward remote regions, long distance pipelines have been actively developed around the world. In order to reduce the total cost of long distance pipeline, need for high strength linepipes has been increased because material and welding cost can be reduced by thinner pipe wall and gas transportation efficiency can be improved by increased operation pressure. Accordingly, the application of high strength linepipes such as API X70 of X80 grade have been increased in recent years, and X100 was put to practical use for the first time in 2002.

On the other hand, construction of the pipeline has expanded to the environmentally severe regions such as cold region, seismic region, deepwater and sour gas environment. Higher deformability is required for the linepipe installed in the seismic or permafrost ground, as well as high strength. Moreover, X70 grade linepipe has been put to practical use for a mild sour environment with lower H_2S content or higher pH, while X60 or X65 grade is mainly used for NACE sour environment. Sour resistant linepipe steels are available by applying advanced steel making and thermo-mechanical controlled processing (TMCP) technologies, and the stable material properties that lead to reliability of the pipeline are required. Moreover, the demand for higher strength heavy wall linepipe has been increased for deep water pipeline, as well. Various material properties in addition to higher strength are required for recent linepipe steel, as mentioned above. JFE Steel has been developing various linepipe products by making good use of advanced material control technology and state-of-the-art steel plate manufacturing equipment.

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

2. Manufacturing Technology of Steel Plate for Linepipe

2.1 Accelerated Cooling Technology

Controlled rolling and accelerated cooling process is usually applied for producing high strength steel plate for linepipe, especially, in order to secure toughness and weldability as well as high strength, accelerated cool-

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ing process plays an important role. JFE Steel has long time experience in TMCP technology, and application of accelerated cooling process to heavy gauge steel plate production was put to practical use in plate mill of West Japan Works for the first time in the world in 1980[1]. In 1998, "Super-OLAC" (on-line accelerated cooling device) was developed and installed in plate mill of West Japan Works (Fukuyama), which theoretically ultimate highest cooling rate was achieved by a new water flow control technology[2]. 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 a great benefit in producing high strength high toughness steels with reduced alloying elements. Steel plates for various linepipe products, such as sour resistant linepipe and X100 grade linepipe, are manufactured by applying such an advanced TMCP technology by state-of-the-art accelerated cooling device.

2.2 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 linepipes, such as sour resistant property and deformability as well as strength and toughness. In order to produce such a high strength and high performance linepipe steels, online heat-treatment process, HOP (heat treatment on-line process), was installed in plate mill of West Japan Works (Fukuyama)[3]. 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. 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 **Fig. 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. On the other hand, in 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 products applied by the HOP process are high strength sour linepipe, high deformability linepipe and high strength pipes for the use of conductor casing and riser. Homogeneous material properties in the thickness direction as well as longitudinal and transverse direction of the plate are obtained by HOP process, resulting in smaller scattering of mechanical properties in the mass production and excellent pipe dimension which is represented by smaller out-of-roundness. Moreover, thermal stability of the material property is increased by the HOP process and this improves heat resistant property, such as stress relief (SR) heat-treatment, and resistance to strain aging.

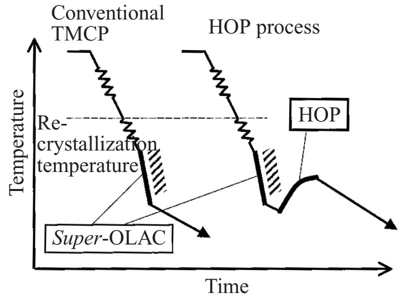


Fig. 1 Schematic temperature profile in plate production process

3. High Strength Linepipe

3.1 X80 Linepipe

JFE Steel started commercial production of X80 linepipe in 1991 for Canadian pipeline project, and has manufactured X80 linepipes that exceeds 50 000 metric tons since then. The statistical data of Charpy absorbed energy for mass produced X80 linepipes is shown in **Fig. 2** as one example of mechanical properties. The averaged value of the base material Charpy energy is 270 J, and this gives excellent crack arrest property. Moreover, even in the cumulative frequency of 1%, base material, heat affected zone (HAZ) and weld metal all show high Charpy energy, showing quite high reliability against fracture.

3.2 X100 Linepipe

In order to comply with the demand for higher

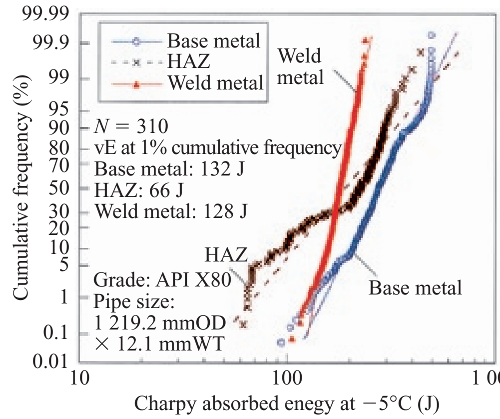


Fig. 2 Weibull distribution of Charpy absorbed energy of X80 linepipe

Table 1 Production results of X100 linepipe (all heat average)

Project	OD (mm)	WT (mm)	Tensile properties (round bar specimen)					Charpy test	DWTT
			Direction	YS (MPa)	TS (MPa)	EL (%)	*Y*/*T* (%)	vE (J) at −5°C	SA% at −5°C
1	1 219.0	14.3	Transverse	763	838	21	91	241	100
			Longitudinal	623	801	22	78	–	–
2	914.4	13.2	Transverse	779	851	22	92	236	100
			Longitudinal	642	816	23	79	–	–

OD: Outer diameter, WT: Wall thickness, YS: Yield strength, TS: Tensile strength, EL: Elongation,
Y/*T*: Yield ratio, vE: Charpy absorbed energy, DWTT: Drop weight tear test, SA: Share area

strength pipeline, JFE Steel produced CSA grade 690 (equiralent to API X100 grade) high strength linepipe in commercial basis for the first time in the world in 2002[4]. In addition, pipeline construction was done in north Canada in the winter of 2004, and good weldability and material performance have been proven[5]. The manufacturing results of the X100 linepipes for the two projects are shown in **Table 1**. Strength meets the specification enough, and Charpy absorbed energy show a high value of 200 J or more. Moreover, in the both projects, high deformability of the linepipe was required considering deformation of the linepipe by ground movement of the permafrost soil, and low value of yield to tensile ratio (*Y*/*T*) that is less than 80% in the longitudinal direction were achieved for both X100 linepipes.

Application of grade X100 linepipe for actual pipeline project is still limited at this moment. However, design, application and evaluation techniques of the high strength linepipe are actively developed as well as material development of X100 grade linepipe, and further usage of X100 linepipe is strongly expected.

4. High Deformability Linepipe

4.1 Needs for High Deformability Linepipe

Strain capacity against large deformation field is required for the linepipe installed in the ground which is expected to induce large plastic straining to the linepipe by ground movement. Linepipes mainly used for domestic pipeline in Japan has the size of diameter to thickness ratio (*D*/*t*) of about 40 which has high deformability with the critical buckling strain by uniaxial compression of 1% or more. However, in the case of applying higher grade linepipe such as X80 grate or more with thinner wall thickness, resistance to buckling of the linepipe tends to decrease. Therefore, improvement of deformability is necessary for applying higher grade linepipe to the practical use. High strength linepipe with excellent deformability that has large buckling strain has developed. Metallurgical controlling techniques and mechanical and buckling properties are introduced in this section.

4.2 Stress-Strain Curve Control Technology for Deformability

For the purpose of developing high deformability linepipe, uni-axial buckling test was carried out using small scale pipes with different mechanical properties, and the relation between stress-strain curve and buckling behavior was investigated, first. **Figure 3** shows the relation between maximum buckling strain and pipe diameter to thickness ratio (*D*/*t*). Maximum buckling strain decreased with increasing *D*/*t*. However, the pipes with round-house type stress-strain curve and with higher *n*-value showed higher buckling strain. Then, optimum microstructure to obtain round-house type stress-strain curve and higher *n*-value (lower *Y*/*T* ratio) was investigated by the analytical methods, such as FEM and

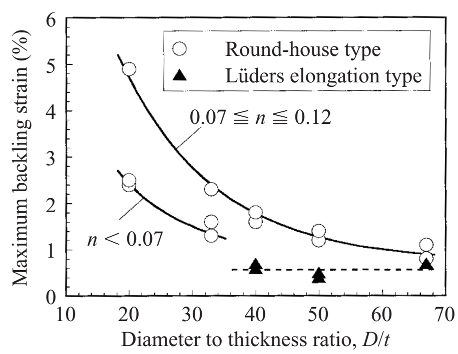


Fig. 3 Relation between maximum buckling strain and *D*/*t* of small scale pipe under uni-axial compression

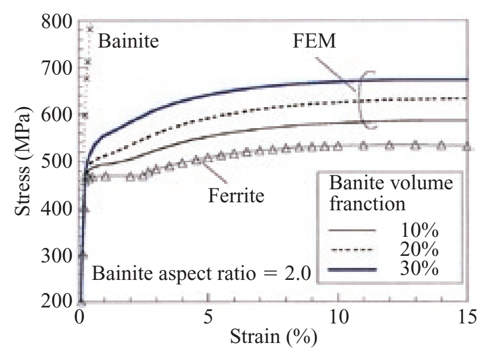


Fig. 4 Effect of bainite volume fraction on stress-strain curves of ferrite-bainite steel by FEM analysis

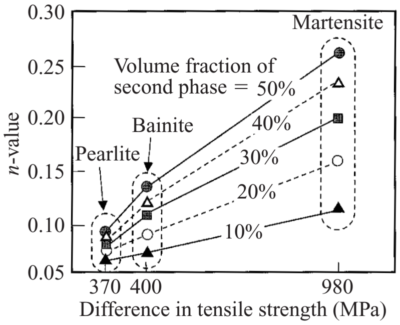


Fig. 5 Effect of difference in tensile strength of each constituent phase on n-value of dual phase steel

Micromechanics. **Figure 4** shows the effect of bainite volume fraction of ferrite-bainite steel on stress-strain curve which was estimated by the FEM analysis with so called "Unit cell model."[6] Ferrite phase itself has a Lüders elongation in the stress-strain curve; however, round-house type stress-strain curve can be obtained by ferrite-bainite two phase microstructure. **Figure 5** shows the analytical result by the Micromechanics models of two-phase microstructure[7]. It is shown that higher n-value can be obtained by increasing volume fraction or strength of second phase. In the case of ferrite-bainite steel, it is known that larger aspect ratio of the bainite phase, i.e. elongated microstructure in the rolling direction, gives higher n-value. Based of the above investigation, the stress-strain curve with round-house type stress-strain curve and higher n-value was achieved by applying controlled rolling and *Super*-OLAC and controlling microstructure of the steel to ferrite-bainite microstructure. High deformability linepipe "JFE-HIPER"[8] has been developed by the concept of controlling stress-strain curve, and morphology of the ferrite-bainite microstructure is optimized depending on the requirement on strength, toughness and deformability.

As shown in Fig. 5, the use of martensite phase as the second phase of two phase steel is more effective to obtain higher n-value, though enough volume fraction of martensite cannot be obtained by the conventional plate production process applying accelerated cooling. However, by applying HOP process, as shown in Fig. 1, martensite-austenite constituent (MA) formation can be controlled, and new type of "JFE-HIPER" with bainite-MA microstructure has been developed[9].

4.3 Characteristic and Production Results of High Deformability Linepipe "JFE-HIPER"

High deformability linepipe "JFE-HIPER" with superior resistance to buckling has developed by multi-phase microstructural control using *Super*-OLAC and optimizing stress-strain curves, and from X52 to X100 grades are available. Examples of mechanical properties of typical grades are shown in **Table 2**. The stress-strain curves in the longitudinal direction are round-house type for all pipes, and high n-value and low Y/T ratio are obtained. **Photo 1** shows microstructure of X65 grade JFE-HIPER. Ferrite-bainite microstructure with optimized bainite morphology provides excellent deformability. Buckling property of the developed linepipes were evaluated by full scale uni-axial buckling test and compared with conventional pipes. **Figure 6** shows the relation between buckling strain and D/t. JFE-HIPER showed higher buckling strain with about 1.5 times

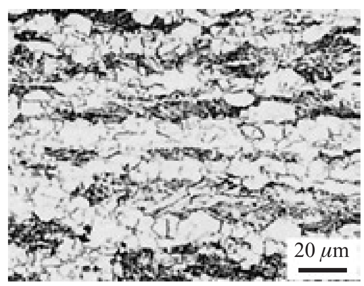


Photo 1 Microstructure of X65 grade JFE-HIPER

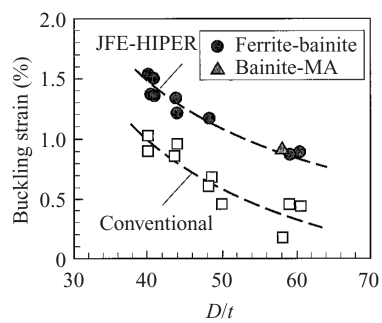


Fig. 6 Relation between maximum buckling strain and D/t of full scale pipes under uni-axial compression

Table 2 Mechanical properties of JFE-HIPER

API grade	Dimention			Longitudinal tensile properties*				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

* Round bar specimen
OD: Outer diameter, WT: Wall thickness, D/t: OD/WT, YS: Yield strength, TS: Tensile strength, Y/T: Yield ratio,
n: n-value, vE_{-10}: Charpy absorbed energy at −10°C, vTrs: Brittle to ductile transition temperature

higher than conventional pipes.

More than 3 000 metric tons of X65 grade JFE-HIPER were manufactured for domestic gas pipeline. For the oversea pipeline project in seismic region, total amount of about 44 000 metric tons of X52 and X60 grade JFE-HIPER were manufactured. Further increase of the demand for high deformability linepipes is expected since pipeline development is expanding toward permafrost or seismic regions. JFE-HIPER is expected to expand its use for other applications such as deepwater pipeline where large deformation is introduced to pipeline.

4.4 HOP Applied JFE-HIPER and Future Development

Bainite-MA microstructure can be obtained by HOP process, besides above mentioned ferrite-bainite microstructure. During the heat treatment after accelerated cooling, carbon concentration into untransformed austenite is promoted, then carbon enriched austenite turns into MA during cooling after heating, thus MA dispersed multi-phase microstructure is obtained. **Photo 2** shows the microstructure of X80 grade JFE-HIPER by HOP process. MA is dispersed in the bainite (or bainitic ferrite) matrix and its volume fraction is about 8%. Mechanical properties of HOP applied X80 grade JFE-HIPER are shown in **Table 3**. Low *Y*/*T* ratio in the longitudinal direction under 80% is obtained same as ferrite-bainite type JFE-HIPER. Full-scale uni-axial buckling test was also conducted for HOP applied JFE-HIPER, and results are plotted in Fig. 6. HOP applied JFE-HIPER with bainite-MA microstructure showed high resistance to buckling same as ferrite-bainite type JFE-HIPER.

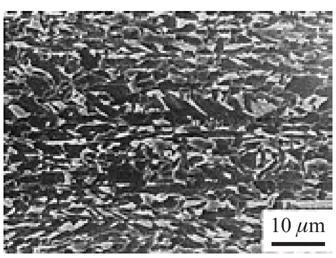


Photo 2 Microstructure of X80 grade JFE-HIPER produced by applying HOP

Table 3 Mechanical properties of JFE-HIPER produced by applying HOP

API grade	Dimention			Longitudinal tensile properties*			
	OD (mm)	WT (mm)	*D*/*t*	YS (MPa)	TS (MPa)	*Y*/*T* (%)	*n*
X80	762	15.6	49	532	702	76	0.12
	1 016	17.5	58	581	734	79	0.14

* Full thickness strip specimen
OD: Outer diameter, WT: Wall thickness, *D*/*t*: OD/WT, YS: Yield strength, TS: Tensile strength, *Y*/*T*: Yield ratio, *n*: *n*-value

Another characteristics of the HOP applied HIPER is resistant to strain aging. In the HOP process, solute carbon content is decreased by carbide precipitation during heating and dislocation density is reduced by recovering of dislocation by tempering of bainite. Recently, there are a lot of discussions about strain aging by the heating during pipe coating which may affect yield strength or *Y*/*T* ratio[10]. However, HOP process can reduce solute carbon and dislocation density which cause strain aging, and it was proved that HOP applied X80 HIPER can keep low *Y*/*T* ratio under 80% even after pipe coating at 240°C. In the oversea pipeline, high temperature pipe coating is becoming popular, and HOP applied HIPER is expected to apply for the linepipe that has resistance to pipe coating.

5. High Strength Sour Linepipe

5.1 Plate Manufacturing Technology for Sour Linepipe by HOP Process

Crack resistant property in H_2S containing environment, hydrogen induced cracking (HIC) and sulfide stress corrosion cracking (SSCC), as well as strength, toughness and weldability is required for sour linepipe. Steels for sour environment is produced by advanced steel making and refinement technology, such as ultra-low sulfur and phosphorus steel making technology, inclusion shape control by Ca addition, and microstructural control technology by *Super*-OLAC. In addition to above mentioned essential techniques, HOP process is applied for the purpose of improving the integrity of the linepipe by adding new feature that cannot be obtained by conventional process. Characteristics of the steel plate produced by HOP are listed as follow;

(1) Homogeneous hardness distribution in through thickness direction
(2) Small scattering of mechanical properties in the plate
(3) Precipitation strengthening by fine carbides
(4) Martensite-austenite constituent (MA) formation control

Figure 7 shows hardness distribution along the plate width of the X60 grade sour linepipe steel produced by HOP process, showing the hardness of surface and quarter thickness portion. It is shown that hardness in the surface and quarter portion are almost the same, moreover, very flat hardness distribution in the plate width was obtained. This is because of homogeneous microstructure which is given by homogeneous temperature distribution in HOP heating process. Accordingly, scattering of the material properties such as strength and toughness can be reduced inside the plate. Moreover,

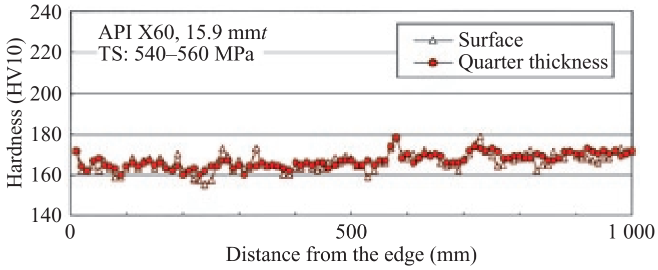
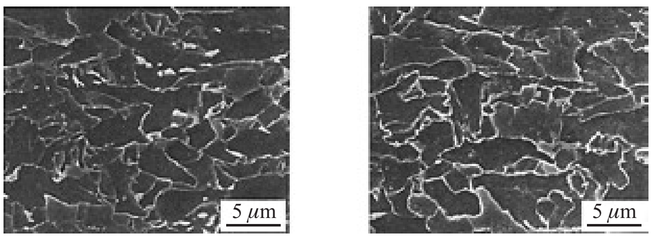


Fig.7 Hardness distribution along the plate width of X60 sour linepipe steel produced by applying HOP



(a) Conventional steel (b) HOP

Photo 3 Microstructure of X70 sour linepipe steel plate produced by conventional TMCP and HOP

formability in UOE process is improved by homogeneous mechanical properties, and this leads to good dimension of the pipe.

HOP applied JFE-HIPER, explained in the previous section, is produced by MA formation control technique by HOP which gives bainite-MA microstructure. However, by the precise control of chemical composition, accelerated cooling and HOP heating conditions, MA formation can be prevented. **Photo 3** shows microstructure of X70 grade sour linepipes. In the conventional TMCP process, MA formation cannot be prevented because of richer chemistry to obtain higher strength, shown in Photo 3(a). On the other hand, HOP applied X70 steel showed quite homogeneous microstructure without MA. As mentioned previously, MA is transformed from carbon enriched austenite during cooling. However, carbon enrichment is prevented by promoting carbide precipitation during HOP heating, resulting in homogeneous microstructure without MA.

5.2 Manufacturing Results of Sour X60 and X65 Linepipe

Application of HOP process to the production of sour linepipes has started in 2004, and more than 40 000 metric tons of X60 and X65 sour linepipes have been manufactured in total, so far.

Figure 8 shows the relation between pipe roundness parameter which is obtained by statistical out-of-roundness data from different pipeline projects, lower value of the roundness parameter means better shape, i.e. lower out-of-roundness, and pipe dimension. As increasing in $D/t^{0.6}$ value, roundness of the pipe deteriorates, however, roundness of the pipe improved by applying HOP process. Moreover, homogeneous hardness distribution in thickness direction can be obtained by HOP process as shown in Fig. 7, and it is possible to comply with the maximum hardness recommendation (hardness should be HV220 or lower) given in DNV OS-F101.

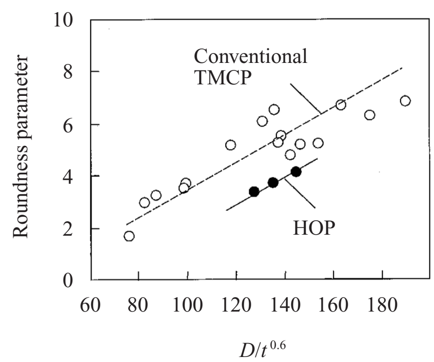


Fig.8 Relation between roundness and $D/t^{0.6}$ for the linepipes with different manufacturing process

Table 4 Chemical compositions of trial X70 sour linepipe

(mass%)

API grade	Chemical compositions						
	C	Si	Mn	P	S	others	Pcm
X70	0.05	0.28	1.13	0.014	0.000 5	Mo,Ni,Cr,Nb,Ca	0.14

Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B

Table 5 Trial production result of X70 sour linepipes by applying HOP

API grade	Pipe number	Tensile properties*1				Impact properties	DWTT	HIC*2	
		YS (MPa)	TS (MPa)	EL (%)	*Y*/*T* (%)	vE (J) at −10°C	SA% at 0°C	CLR (%)	
								90°	180°
X70	1	531	613	23	87	373	100	0, 0, 0	0, 0, 0
	2	523	600	22	87	343	100	0, 0, 0	0, 0, 0

*1 ISO lecutanglar specimen, trans. direction
*2 NACE TM0284-solution A
YS: yield strength, TS: tensile strength, *Y*/*T*: Yield ratio, EL: Elongation, vE: Charpy absorbed energy,
DWTT: Drop weight tear test, SA: Share area, HIC: Hydrogen induced cracking, CLR: Crack length ratio

5.3 Trial Production Result of Sour X70 Linepipe

As increasing in alloying elements, brittle phases such as MA tend to form in the steel by conventional TMCP process, and these brittle phases enhance crack propagation in HIC test. Therefore, control of brittle phases such as MA is the key issue for developing higher strength sour linepipe. By applying HOP process, which homogeneous microstructure without MA can be achieved, trial production of X70 grade linepipe (914.4 mmOD × 19.1 mmWT) was conducted. **Tables 4** and **5** show chemical composition, mechanical properties and HIC test results of the trial pipes. Enough strength and toughness were obtained and no crack was observed in HIC test with NACE solution A.

Further production tests will be conducted, aiming to early practical use of the X70 sour linepipe in the future.

6. Conclusion

Further development of natural gas pipeline is expected based on increased energy demand in the world, and demand for higher strength linepipe with various material properties depending on the environment where the pipe installed should be a continuous trend. In addition, it is necessary to pay the maximum attention to the reliability of the linepipe material in order to secure the integrity of long distance pipelines. In order to comply with these needs for linepipes, JFE Steel has been developing high performance linepipes, such as X100 grade linepipe, JFE-HIPER, high strength sour registant linepipes, and so on. It is convinced that these high strength linepipe products will contribute to stable supply of natural gas in the world.

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