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High Strength Linepipe with Excellent HAZ toughness

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1. Abstract

The API 5L-X65 steel plates for low temperature service were produced using the thermo-mechanical control process (TMCP) with the optimum micro-alloying addition. Featuring of the additions are as low amount of titanium, calcium, niobium, and vanadium as possible, for high heat affected zone (HAZ) toughness and strength. Controlling titanium and nitrogen and the Ti / N ratio, a large number of TiN dispersed finely are formed in steel and the austenite grain size near a weld fusion line is refined remarkably owing to strong pinning effect of TiN. Calcium addition promotes ferrite nucleation, so that increase in fine polygonal ferrites makes microstructure of HAZ much finer. Niobium and vanadium content are reduced, because carbide precipitates are formed when the coarse grain HAZ is reheated around 700 degree C and the precipitation hardening deteriorates HAZ toughness. The trial manufacturing of the 19.5mm, 26.9mm and 31.4mm thick X65 grade UOE pipes was finalized with the satisfactory results. The toughness of longitudinal submerged-arc welds was more than 50 J in Charpy V-notch impact test at -30°C.

2. Introduction

As the exploration of oil and gas fields are expanding toward severe environment regions, requirements for the performance of linepipes has been diversified and has become stringent. Recent study indicated the significant advantages of using higher strength linepipes in constructing long distance pipelines [1], because it can improve transportation efficiency of gas and oil pipelines by increasing internal pressure, and material cost can be saved by reducing wall thickness of pipe body and consumable of weldment. Another severe requirement for the pipes these days is to ensure low temperature toughness of welded region, such as Heat Affected Zone (HAZ) and weld metal, as well as parent material. The parent material of linepipe is usually manufactured by using TMCP (Thermo-Mechanical Controlling Process) technique. Accelerated cooling techniques gives significant advantages in improving strength and toughness of parent materials through controlling their microstructure to be fine shape, and this led to a considerable increase in the number of applications for manufacturing the higher strength linepipes in this decade.

However, the fine microstructure that has been developed by TMCP can not exist in HAZ, because HAZ is exposed in high temperature during welding. This microstructural change often brings deterioration effects in toughness of HAZ. In case of heavier wall linepipes than 20mm, testing temperature reduction rule is often applied. This means testing temperature for Charpy V test should be –20 to –30 degree C for the heavier wall linepipes even when their service temperature is –10 degree C. In this sense, importance to ensure superior HAZ toughness for the heavier wall materials is highlighted. To ensure the superior toughness of HAZ, the effects of alloying elements, such as Ti, N, Ca, Nb V and Oxygen on microstructure of HAZ in terms of suppressing grain coarsening in HAZ, introducing ferrite nucleation sites and suppressing formation of M-A constituents in HAZ have been investigated.

In this paper, these design concepts of manufacturing X65 linepipes by UOE process were described in relation to the effects of micro-alloying elements on the microstructure evolution in HAZ and resulting toughness. According with the investigation results, trial productions of the pipes with wall thickness of 19.5, 26.9 and 31.4mm were made. The mechanical properties of the X65 grade linepipes were also presented.

3. Design concept of improving HAZ toughness

It is known that the HAZ toughness is affected by austenite grain size [2],[3], kind of microstructure[4], volume fraction of martenseite – austenite (M-A) constituents[5]. These metallurgical features can be controlled by micro alloying of steels. So, the effects of chemical compositions on the toughness of HAZ were studied using synthetic weld thermal cycle Charpy test. Table 1 shows the chemical compositions of the steel studied. Figure 1 shows the schematic illustrations of synthetic weld thermal cycle patterns. The cooling condition was equivalent to the actual longitudinal seam submerged arc welding. The peak temperature were set at those of coarse grained HAZ (CGHAZ) and the sub critical coarse grained HAZ (adjacent to the fusion line of the weld).

Effect of TiN on austenite grain size and resulting toughness of CGHAZ

Fine dispersed TiN precipitations are useful to prevent the austenite grain growth by pinning effect. Figure 2 shows the solubility predicts of TiN calculated by equation (a)[3].

$$\text{Log}\,[Ti][N] = 0.322 - 8000 / T \qquad \text{(a)}$$

[Ti] : Titanium content [mass%]
[N] : Nitrogen content [mass%]
T : temperature [K]

The solution temperature increases with the increase in titanium and nitrogen content. Furthermore, the Ti / N ratio affected on size of TiN particles at higher temperature. Figure 3 shows the SEM observation results of TiN distribution of the steels after synthetic CGHAZ thermal cycle. The size of TiN particles of the steel whose the Ti / N ratio was 2.7 is much finer than that of the steel whose the Ti / N ratio was 3.8. Figure 4 shows the effect of the Ti / N ratio of steels on the austenite grain size and Charpy fracture appearance transition temperature (FATT) of synthetic CGHAZ. The austenite grain of synthetic CGHAZ was refined remarkably by lowering the Ti / N ratio, so that the toughness of the synthetic CGHAZ was improved.

Table 1 Chemical compositions of steels studied. *(mass%, *ppm)*

	C	Si	Mn	P	S	Al	Nb	V	Ti	Ca*	N*	Others	Ti/N	Pcm
Conventional	0.08	0.28	1.52	0.01	0.003	0.03	0.04	0.05	0.012	tr.	28	Cu,Ni	4.3	0.172
studied	**0.05 – 0.08**	0.20	1.55	0.01	0.003	0.03	**0.03 – 0.04**	**tr. – 0.05**	**0.011 – 0.016**	**tr. – 40**	**40 – 57**	Cu,Ni	**2.0 – 3.8**	**0.166 – 0.177**

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

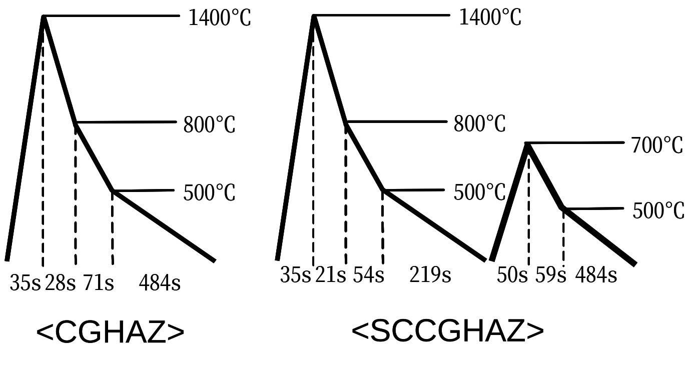


Fig. 1 Schematic illustration of thermal cycle pattern for investigation of HAZ.

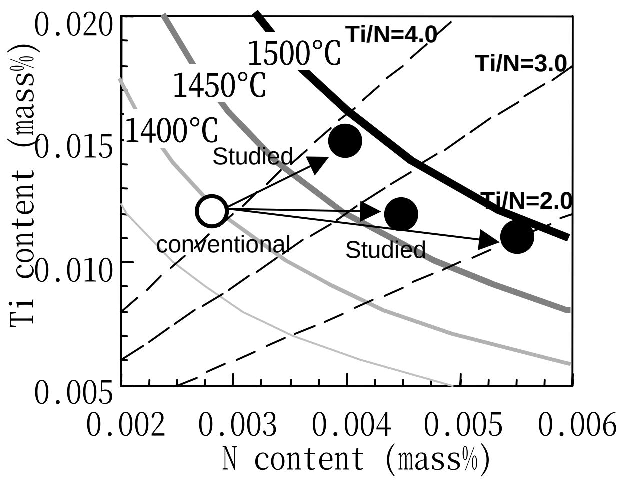


Fig. 2 Calculated results of solid solution temperature of TiN.

Effect of Ca on microstructure and resulting toughness of CGHAZ

It is known that some inclusions act as specific heterogeneous nucleation site of austenite – ferrite transformation. In order to refine CGHAZ microstructure by promotion of fine polygonal ferrite nucleation, the effect of calcium addition was studied.

Figure 5 shows the relation between calcium content and Charpy FATT of synthetic CGHAZ. Toughness of the synthetic CGHAZ was improved by calcium addition up to 30ppm. Figure 6 shows the microstructures of the synthetic CGHAZ whose calcium content is 0ppm and 20ppm. In case of the calcium free steel, the CGHAZ microstructure was only upper bainite. On the other hand, fine polygonal ferrite can be observed in the CGHAZ microstructure of the 20ppm calcium added steel. Figure 7 shows an example of inclusion in the 20ppm calcium added steel. It can be seen a complex particle consisting of Ca (O,S) with MnS, Al_2O_3, and TiN. It is

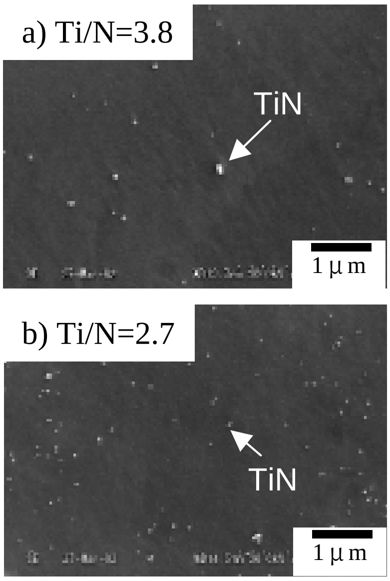


Fig.3 SEM observation results of TiN in CGHAZ.

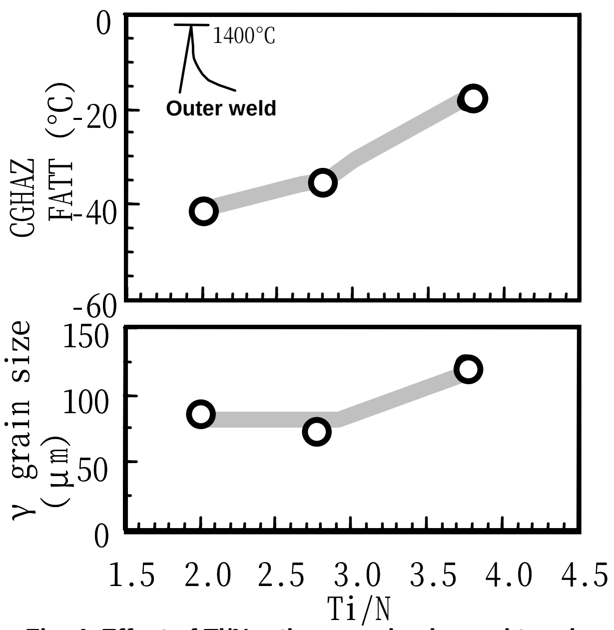


Fig. 4 Effect of Ti/N ratio on grain size and toughness of CGHAZ.

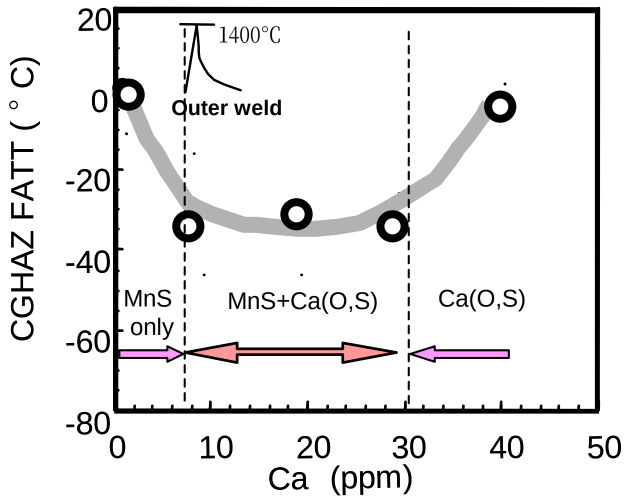


Fig. 5 Effect of Ca content on CGHAZ toughness.

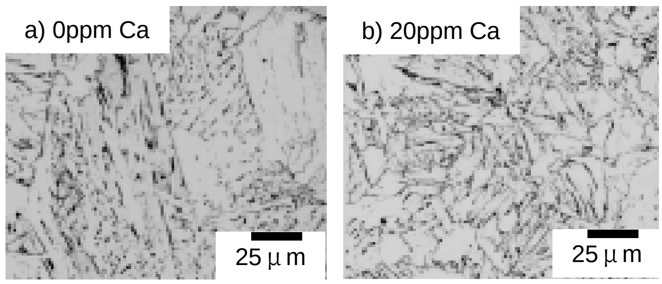


Fig. 6 Effect of Ca addition on CGHAZ microstructure.

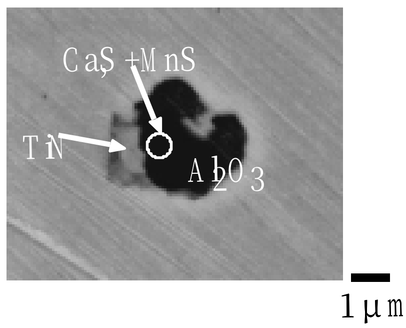
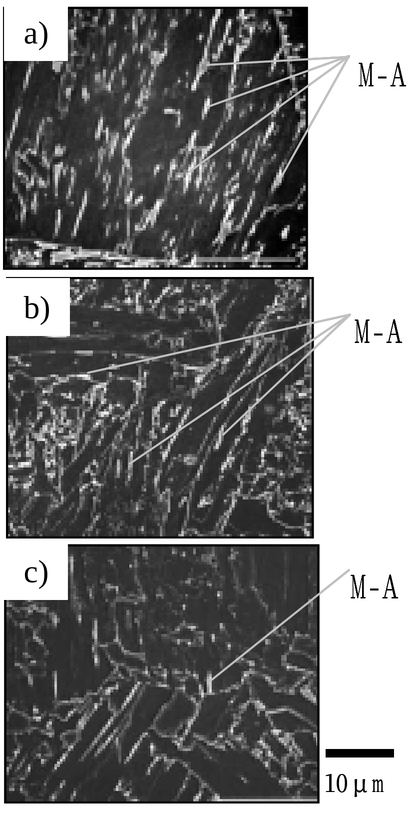


Fig. 7 TEM observation results of inclusion in CGHAZ.

considered that the inclusions which consist of Ca (O,S) with MnS act as the nucleation site of polygonal ferrite. However the inclusions consisted of only Ca (O,S) does not act as the nucleation site, so that the toughness of CGHAZ is not improved in case of the steel whose calcium content is over 30ppm.

Decrease in volume fraction of M-A constituents of CGHAZ

Fig. 8 shows the SEM observation results of synthetic CGHAZ microstructure. The conventional X65 steel whose carbon, niobium, and vanadium contents were 0.08, 0.045, and 0.051mass%, respectively, exhibits typical upper bainaite. Also, a lot of M-A constituents can be seen. The amount of M-A constituents of low carbon steel whose carbon content was 0.05mass%, was less than that of the conventional X65 steel. Furthermore, lowering niobium and vanadium content of steel was more effective to reduce the amount of M-A constituents. Fig. 9 shows the results of Charpy impact test of synthetic CGHAZ. The value of FATT was improved due to the lowering carbon, niobium, and vanadium content.



a) 0.08C-0.045Nb-0.051V
b) 0.05C-0.045Nb-0.058V
c) 0.06C-0.03Nb-0.03V

Fig. 8 SEM observation results of M-A constituents in CGHAZ.

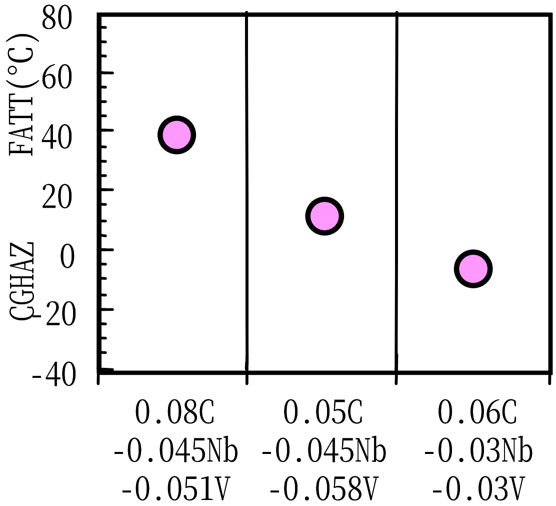


Fig. 9 Effect of C,Nb,V content on CGHAZ toughness.

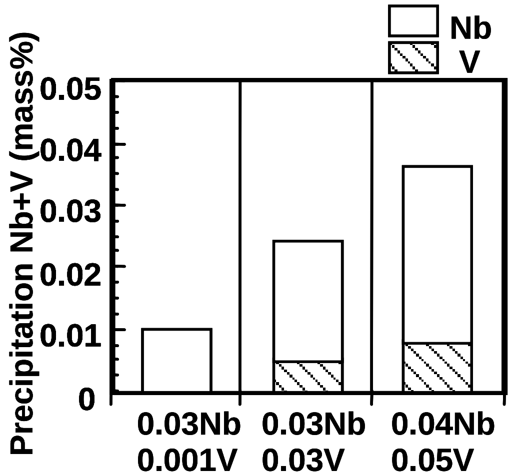


Fig. 10 Amount of precipitation in SCCGHAZ.

Effect of Nb, V content on precipitation hardening and

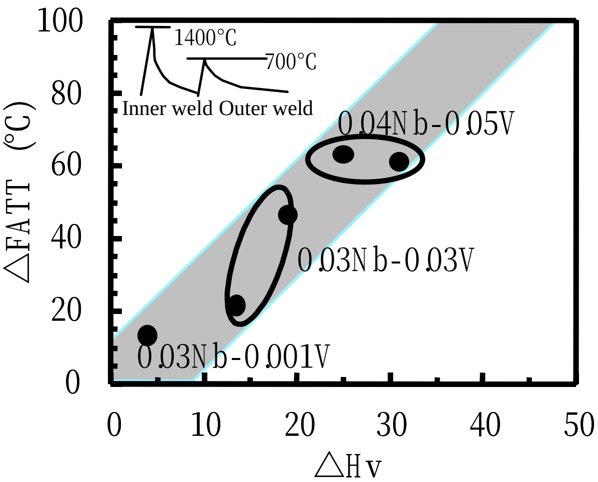


Fig. 11 Relationship between hardness and toughness of SCCGHAZ.

toughness of SCCGHAZ

In case of inner side of the longitudinal seam weld near fusion line, the dissolved carbide or nitride in CGHAZ precipitate again through the second thermal cycle by the outer weld. Figure 10 shows the amount of niobium and vanadium precipitation of the steels whose niobium and vanadium contents were varied after SCCGHAZ cycle. The amount of Nb precipitates increased with the increase in niobium content of the steel. The amount of V precipitates is less than that of Nb precipitates, but the Nb precipitates increased by the simultaneous addition of vanadium. Figure 11 shows relationship between the increases in the HAZ hardness and the increases in the HAZ Charpy FATT by comparing CGHAZ and SCCGHAZ. The SCCGHAZ toughness deteriorated with the increase in the SCCGHAZ hardness. Lowering niobium and vanadium content of steels suppresses the deterioration of SCCGHAZ toughness due to the reduction of amount of precipitation.

4. Trial production of X65 UOE pipes

Chemical Composition

The chemical composition of steel is shown in Table 2. In order to reduce the volume fraction of M-A constituents, carbon content was 0.06 mass%. Also, in order to reduce the M-A constituents, and suppress the precipitation hardening at SCCGHAZ, niobium content was 0.03 mass% and vanadium was not added. The Ti / N ratio was controlled to be 3.2 in order to prevent coarsening TiN particles. Calcium was added but controlled to be below 30ppm. The Pcm value was 0.171 mass% with micro alloying element of cupper and nickel.

Plate Rolling

The steels having chemistry in Table 2 were control-rolled to plates of 19.5 mm, 26.9mm and 31.4 mm in thickness from continuously cast slabs followed by the accelerated controlled cooling (ACC). The controlled-rolling is an essential process to the refinement of microstructure, which gives high toughness together with high strength. In addition, the ACC after the controlled-rolling leads to the further increase in the strength through further refinement of microstructure associating with the suppression of ferrite formation.

Manufacturing of Pipes

Test productions of X65 UOE pipes were carried out. The pipes were 914 mm in diameter and 19.5 mm, 26.9mm and 31.4 mm in thickness. Straight seams of pipes were welded from the inside first and subsequently from the outside. The heat inputs for the outside passes were 4.2 kJ/mm for the 19.5 mm-thick pipe, 6.7 kJ/mm for the 26.9 mm-thick pipe, and 8.4 kJ/mm for 31.4 mm-thick pipe.

Table 2 Chemical compositions of X65 steel manufactured. *(mass%, *ppm)*

C	Si	Mn	P	S	Al	Nb	V	Ti	Ca*	N*	Others	Ti/N	Pcm
0.06	0.15	1.57	0.01	0.002	0.04	0.03	0.002	0.016	14	47	Cu,Ni	3.2	0.171

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

Table 3 Mechanical properties of pipe body.

Thickness (mm)	Tensile properties YS (kN/mm^2)	TS (kN/mm^2)	YR (%)	El (%)	CVN vE-30 (J)	DWTT SATT (°C)
19.5	500	596	84	42	445	-55
26.9	505	605	83	49	441	-50
31.4	545	660	83	50	430	-47

Table 4 Mechanical properties of longitudinal seam weld.

Thickness (mm)	Weld tensile test: TS (kN/mm^2)	Weld tensile test: Fracture Position	Fusion line CVN: position	Fusion line CVN: vE-30 ave. (J)	Fusion line CVN: SA-30 ave. (%)
19.5	603	Base metal	outer	398	96
			root	461	100
26.9	628	Base metal	outer	338	84
			root	451	100
31.4	641	Base metal	outer	280	76
			root	427	95

Mechanical Properties of Pipes

Mechanical properties of pipes are summarized in Table 3. Satisfactory values for both yield and tensile strength were shown. Ratios of yield strength to tensile strength, YR, were less than 85 % for both pipes.

The values of Charpy absorbed energy at –30deg.C were over 400J. The values for 85% SATT in drop weight tear test (DWTT) of Battelle type were below –30deg.C and indicate the good resistance to brittle fracture propagation.

Toughness of Straight Seam Welds

The toughness of seam welds of pipes is shown in Table 4. The average of fusion line Charpy absorbed energy of each pipes were enough high at –30degree C. Figure 12 shows the Weibull type distribution of absorbed energy and shear area, which are plotted against cumulative frequency. In case of 31.4mm wall thick pipe, the absorbed energy at 5%cumulative frequency was indicated 50J. And the value of 19.5mm wall thick pipe was much higher. This suggests that the developed X65 UOE pipes which were designed not only to refine CGHAZ microstructure but also to suppress the formation of M-A constituents and Nb,V precipitation, proved their excellent toughness.

5. Conclusions

API X65 grade high strength linepipes have been developed applying the controlled rolling followed by accelerated cooling process. To ensure the superior toughness of HAZ, the effects of alloying elements, such as Ti, N, Ca, Nb V and Oxygen on microstructure of HAZ in terms of suppressing grain coarsening in HAZ, introducing ferrite nucleation sites and suppressing formation of M-A constituents have been investigated.

The main results are summarized as follows;

(1) Increasing the titanium and nitrogen content with controlling the Ti / N ratio, the CGHAZ microstructure can be refined by pinning effect of fine dispersed TiN particles.

(2) Optimum calcium addition promotes the polygonal ferrite nucleation and refining the CGHAZ.

(3) Lowering C,Nb,V suppress the formation of M-A constituents at the CGHAZ.

(4) Lowering Nb,V suppress the precipitation hardening and deterioration of SCCGHAZ.

(5) Manufactured X65 UOE pipes whose wall thickness is 19.5mm, 26.9mm, and 31.4mm exhibit not only enough strength and toughness of base metal for specification but also excellent HAZ toughness.

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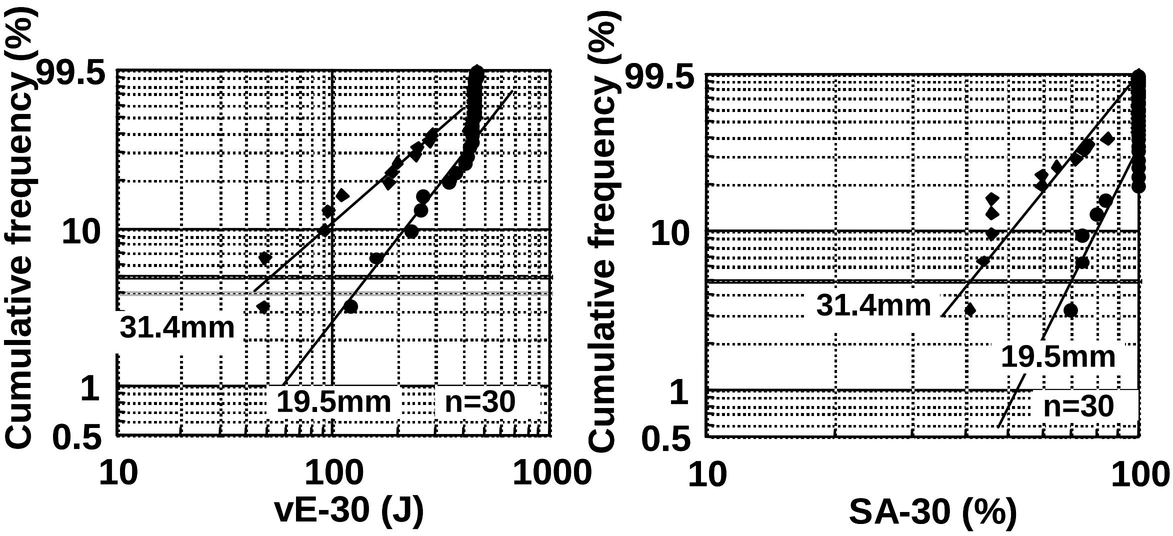

Fig. 12 Weibull distribution of fusion line Charpy test results.