Development of 150mm Thick HT980Z Steel Plate

by

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Synopsis

The pumped storage hydroelectric power station will be constructed in places which have larger capacity and higher water head. This maybe led to the consideration for the use of HT980 in penstock and bifurcation. 150mm thick HT980Z steel plate was researched and developed assuming that to be the maximum thickness for sickle plate for the Escher Wyss-type bifurcation. This newly developed heavy thick HT980Z had uniform, excellent mechanical properties of base metal and satisfied target properties such as weldability, weld joint properties and brittle fracture properties. Heavy thick HT980Z shows sufficient fracture safety in the case of use the sickle plate of the Escher Wyss-type bifurcation, and also shows excellent characteristics as high strength steel plate from the aspect of cost performance as well as structural design.

1. Introduction

125mm thick HT590 steel plate was first applied in Japan for the internal reinforcement (called sickle plate) for the Escher Wyss-type bifurcation at Okuyahagi No. 1 Hydroelectric Power Station, Chubu Electric Power Company Inc.. Subsequently the thickness was increased to 150mm at Shimogo Hydroelectric Power Station and 189mm at Mingu-Hu Hydroelectric Power Station. 175mm thick HT780 steel plate was first applied at Okumino Hydroelectric Power Station.

The pumped storage hydroelectric power station will tend to be larger capacity and higher water head. In such a case, HT980 may be used as a substitute for HT780 in order to reduce wall thickness and to save construction costs, transportation costs and construction period[1].

Based on the research concerning HT980 steel plate for penstock main pipe up to 100mm[2)~6)], 150mm thick HT980Z for sickle plate for the Escher Wyss-type bifurcation was studied and developed required properties different from these of penstock main pipe. (Sumitomo's brand name : SUMITEN950Z, thickness assumed to be maximum thickness of sickle plate)

This paper introduces the properties of 150mm thick HT980Z steel plate and a safety evaluation as sickle plate for the Escher Wyss-type bifurcation, and also introduces the advantage of adoption of HT980 in comparison with that of HT780[7)-8)].

2. Target Properties of 150mm Thick HT980Z Steel Plate

Target properties of 150mm thick HT980Z steel plate are shown in **Table 1**.

Table 1 Target properties of 150mm thick HT980Z steel plate

Item		Target values
Mechanical properties of base metal	Yield strength	≧865 N/mm²
	Tensile strength	930～1110 N/mm²
	Elongation	≧12%*
	Reduction of area of through thickness direction	≧25%*
	Charpy fracture transition temperature	≦−60°C
	Charpy absorbed energy	≧47 J (−60°C)
Weldability	Preheating temperature to prevent cold cracking	≦150°C
Mechanical properties of welded joint	Tensile strength	≧930 N/mm²
	Charpy absorbed energy	≧55 J (0°C)

* JIS Z 2202 No. 4 test specimen

2.1 Strength of Base Metal

Basically HW885 of WES3001 (1983) "Weldable High Strength Steel Plate" was reffered to. But plate thickness largely exceeds the scope of WES3001 whose maximum thickness is 75mm. Therefore the target values for both yield strength and tensile strength were decreased by 20N/mm².

2.2 Impact Properties of Base Metal

Based on the basic concept that base metal should have "arrestability to brittle fracture propagation at 0°C", study made whether WES3003 (1983) "Evaluation Criterion of Rolled Steels for Low Temperature Application" A-use criteria can be used in the case of exceeding the scope where maximum thickness is 100mm with HT780. As a result, the Kca-vTrs correlation function is applicable to HT980 as shown in **Fig. 1.** Futhermore, as shown in **Fig. 2**, WES3003 A-use criteria is applicable up to 150mm thick steel plate because of the saturation of the thickness effect on Kca-Thickness relation. The target vTrs value of base metal was calculated by applying the following conditions to WES3003 A-use criteria.

(1) Minimum service temperature=0°C
(2) Working stress=365N/mm²
(3) Allowable stress (σ_y/S・α)
S (Safety factor)=1.8
α (Material factor)=1.3

Target values : vTrs ≦ −60°C

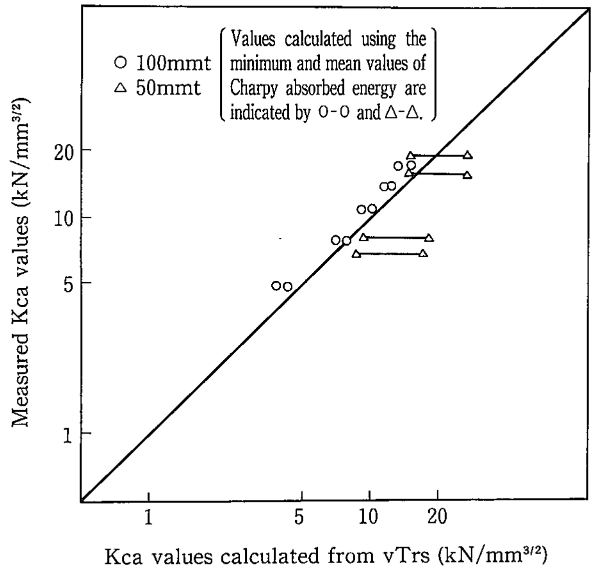


Fig. 1 Comparison of measured Kca values and Kca values calculated from Charpy fracture transition temperature vTrs in WES3003, A-use criteria

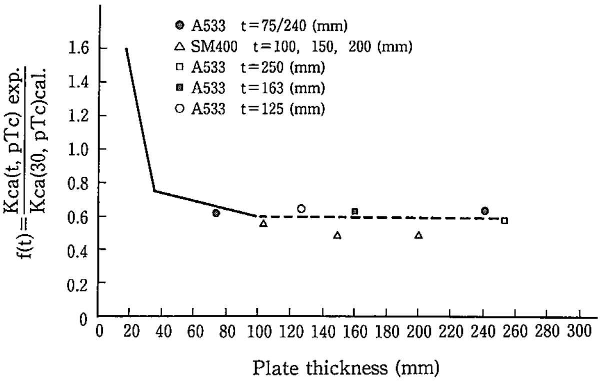


Fig. 2 Thickness effect on Kca in the thickness range over 100mm

2.3 Weldability

Welding of the sickle plates for the Escher Wyss-type bifurcation is usually executed at shop, where quality control of welding is easily attained than at site. The minimum preheating temperature to prevent cold cracking, therefore, was settled at 150°C, instead of 125°C normally employed for welding in tunnel.

2.4 Tensile Strength of Welded Joints

Tensile strength of welded joints was set at the same as the specified tensile strength of base metal.

2.5 Impact Properties of Welded Joints

Impact properties of welded joints are based on the basic concept that brittle fracture should not be initiated at 0°C. First, the applicability of WES3003 (1983) G-use criteria to the 150mm thick HT980 welded joint was studied because these application conditions were out of the scope of the standard where the maximum thickness is 100mm with HT780. As a result, it was found that it was not proper to apply the criteria which is the standard for base metal, and concluded that criteria based on WES2805 (1980) "Method of Assesment for Defects in Fusion Welded Joints with respect to Brittle Fracture" was suitable. The criteria were determined in the following sequence.

(1) The investigated weldment and location of the assumed flaw

Sections where sickle plates were welded on pipe shell as shown in **Fig. 3** were selected, and assumed flaw was set.

(2) Prerequisites for calculation

Working stress and misalignment of bifurcation were set in accordance with "Japanese Technical Standard for Water Gates and Penstocks", and the conditions for calculation were provided as follows.

- Misalignment (angular distortion : 2.5°, off-set : 3mm)
- Strain intensity factor (1.5)
- Dimension of a virtual flaw (size of surface defect is 15mm in both depth and width)
- Residual stress due to welding (maximum value : 865N/mm², that is nominal yield strength)

(3) Calculation of required toughness values

Fracture toughness value (critical CTOD value at 0°C) required for welded joint corresponding to the investigated weldment and assumed flaw is calculated. This is then converted to the vEo value of Charpy absorbed energy, and the most extreme value is adopted as the target value.

Target value : vEo ≧ 55J

[Required critical CTOD value at 0°C : 0.106mm]

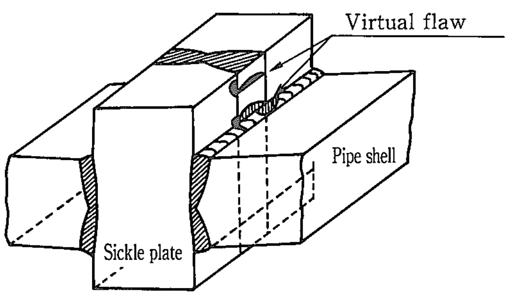


Fig. 3 Investigated weldment and virtual flaw[8)]

3. Fundamental Study

3.1 Required Hardenability

In order to obtain sufficient strength and toughness in the center of the plate, proper hardenability is required for heat treatment. Concerning ideal critical diameter value D_I which shows as an index for hardenability, the minimum value required for securing toughness for each plate thickness can be obtained as shown in **Fig. 4**. As a result, the value of D_I for a 150mm thick steel plate was set at more than 300.

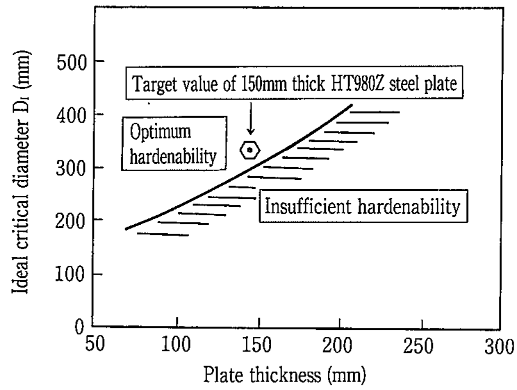


Fig. 4 Required hardenability in order to obtain superior toughness up to the center of the plate thickness

$$\left(D_I = 0.311 \times \sqrt{C} \times (1+0.64Si) \times (1+4.10Mn) \times (1+0.27Cu) \times (1+0.52Ni) \times (1+2.33Cr) \times (1+3.14Mo) \times 25.4 (mm) \right)$$

3.2 Amount of Ni Addition

As a result of studying the amount of Ni addition from the viewpoint of preheating temperature reduction and superior toughness and arrestability of brittle fracture, it becomes clear that higher Ni addition was advantageous to all properties. **Figure 5** shows the influence of the Ni addition on improvement of A-use temperature. The figure also shows that A-use temperature becomes lower with the increase of Ni addition even if vTrs is the same. Also, as shown in **Fig. 6**, increasing the Ni addition has a large effect on lowering the preheating temperature. This improvement of cold cracking susceptibility probably is owing to the reduction of restraint stress by lowering transformation temperature. In addition to these results, the amount of Mn and Ni addition was adjusted from the viewpoint of securing the required hardenability for 150mm thick steel plate based on the chemical composition of 100mm thick HT980 steel plate. Taking cost into account, ultimately target value of the amount of Ni addition was determined to be 3.8%. **Figure 7** shows a comparison with HT780 steel.

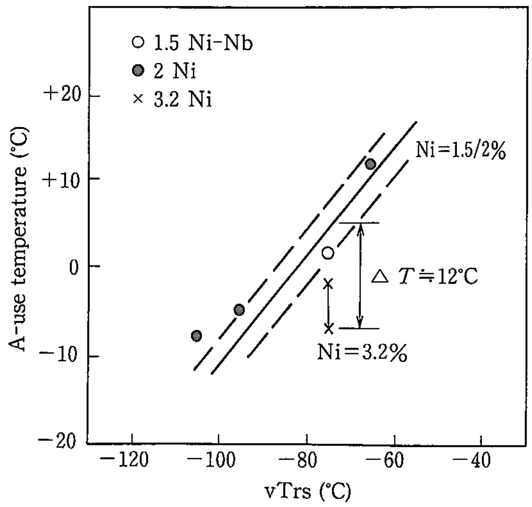


Fig. 5 Relation between A-use temperature and vTrs

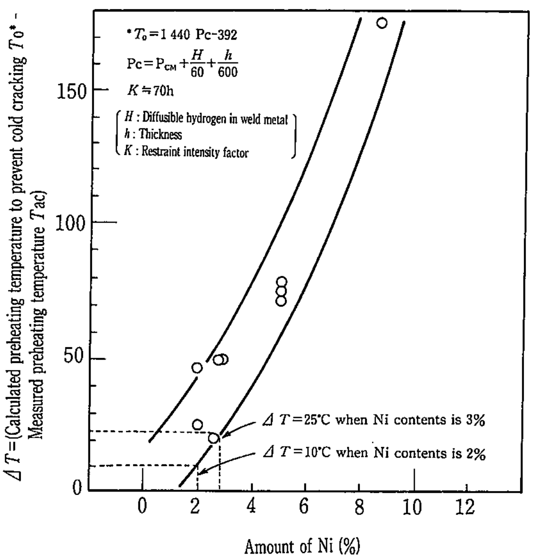


Fig. 6 Effect of Ni addition on ΔT

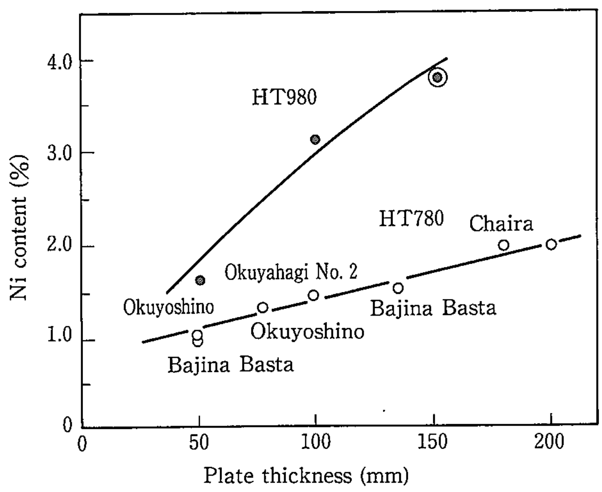


Fig. 7 Relation between Ni contents and plate thickness

3.3 Small Amount of Nb Addition

Figure 8 shows the relation between austenite grain size and vTrs compared with the effect of Nb addition to HT980 steel plate. Small amount of Nb addition improves the balance between strength and toughness by austenite grain size refinement, and has effects such as enhancing toughness of the surface and increasing temper softening resistance. Furthermore, if Nb addition is 0.03%, and under, it has already been confirmed that it has no deterioration effect on the weld cracking susceptibility and toughness of welded joints of HT980[6], so it was decided to add small amount no more than 0.02%. of Nb

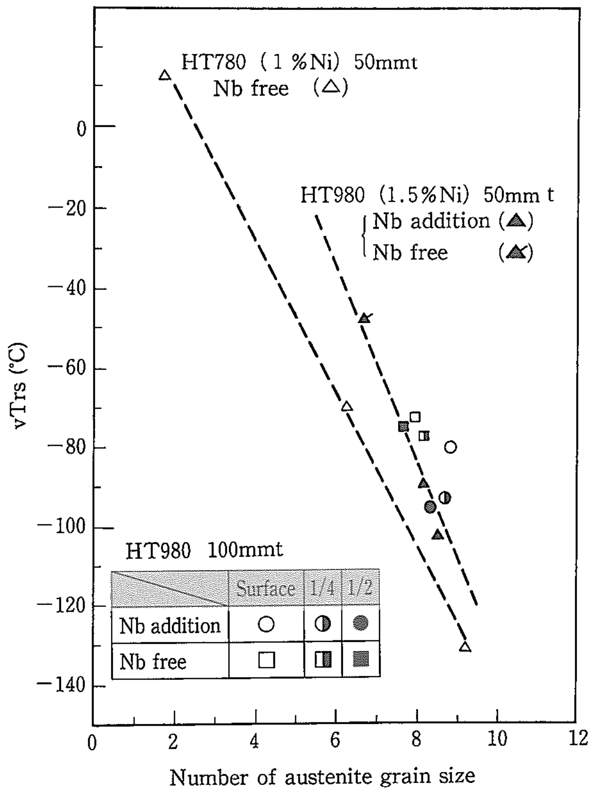


Fig. 8 Effect of austenite grain size on vTrs of 100mm thick HT980

4. Properties of 150mm Thick HT980Z Steel Plate

4.1 Manufacturing of Base Metal

Target values of chemical composition were decided based on the results given in chapter 3. In order to obtain super-clean steel and superior properties in the thickness direction of heavy thickness steel plate, non-metallic inclusions and impurities such as P and S were reduced by taking refining process, such as SRP (Sumitomo's Simple Refining Process), KR (Kanbara Reactor), LF (Ladle Furnace) and RH vacuum degassing equipment.

4.2 Properties of Base Metal

The chemical composition is shown in **Table 2**, and the mechanical test results are shown in **Table 3.** The satisfactory results were obtained for target of mechanical properties of base metal. The microstructure is shown in **Photo 1**. The photograph shows the mixture of fine grain tempered martensite and lower bainite. Steel quality was confirmed to be extremely clean and homogeneous.

Table 2 Chemical composition of 150mm thick HT980Z steel plate

Analysis	Thickness position	Chemical composition												Ceq(1)	Pcm(2)
		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb	B		
Ladle	–	0.13	0.06	1.02	0.003	0.001	0.24	3.90	0.55	0.58	0.030	0.013	0.0013	0.66	0.34
Check	1/4 t	0.14	0.05	1.03	0.004	0.001	0.23	3.80	0.56	0.58	0.027	0.012	0.0011	0.67	0.34
	1/2 t	0.14	0.05	1.04	0.004	0.001	0.23	3.78	0.56	0.58	0.028	0.013	0.0011	0.67	0.34

Notes (1) $Ceq = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$ (%)
(2) $Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$ (%)

Table 3 Mechanical properties of base metal

Direction	Thickness position	Tensile test				Charpy impact test	
		YS (Yield strength)	TS (Tensile strength)	El (Elongation)	RA (Reduction of area)	vE_{-60}	vTrs
		N/mm²		%		J	°C
L	Surface	–	–	–	–	184	−98
	1/4 t	897	951	23.2	70.4	202	−90
	1/2 t	904	958	23.3	69.6	186	−113
C	Surface	–	–	–	–	172	−88
	1/4 t	915	971	21.9	68.7	164	−106
	1/2 t	907	964	19.8	67.8	173	−109
Z	1/2 t	–	961	–	62.0	125	−80

Note) Ingot position : Top

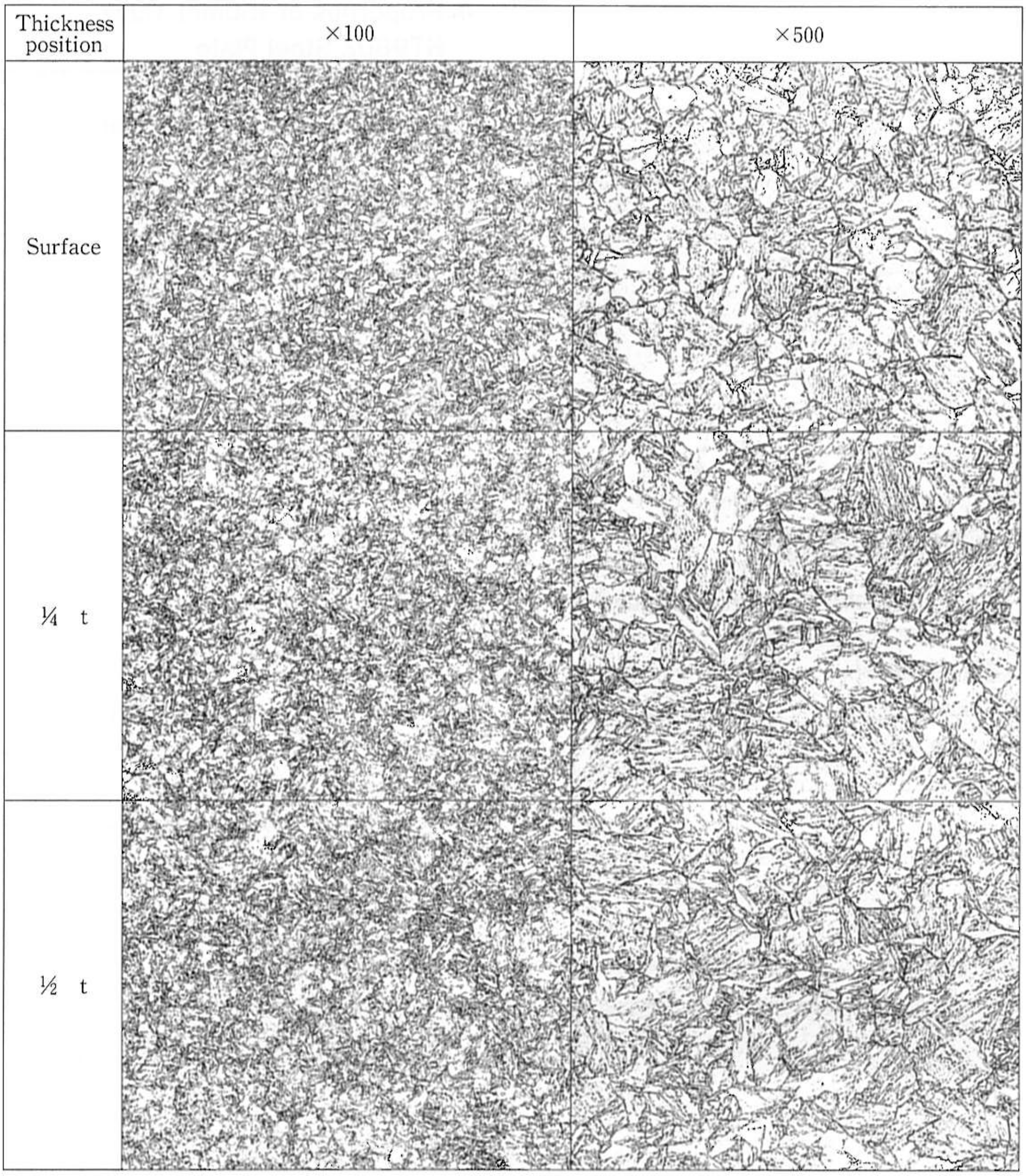


Photo 1 Microstructure of base metal

4.3 Weldability

Along with evaluation of hardenability of the heat affected zone (HAZ) with the maximum hardness test and taper hardness test, y-groove and U-groove restraint cracking tests were conducted to study the properties of weld cracking of base metal and weld metal. As a result, no cracking was confirmed at a preheating temperature of 75°C even when with weld material at moisture absorption condition (keep for 1 hr. in 80% humidity atmosphere at 30°C). The previously mentioned, effect of Ni probably contributes to this results. The preheating temperature to prevent cold cracking in the U-groove restraint cracking test was 100°C for both moisture absorption and dry conditions. With HT980, it is therefore required to take weld cracking susceptibility of the weld metal into consideration when determine the preheating temperature.

The Z-window type restraint cracking test was conducted to study the lamellar tearing susceptibility required for sickle plate, and absolutely no lamellar tearing was confirmed. Probably superior plate thickness direction properties of base metal will largely contribute to superior lamellar tearing properties.

4.4 Properties of Welded Joint

Strength, toughness, hardness distribution, and soundness of the welded joint of submarged arc welding (SAW) were studied. Test results well in excess of target values, it was confirmed that the welded joint was satisfactory.

Table 4 Mechanical properties of welded joint in SAW

Thickness position	Tensile test	Side bend test 180°	Charpy impact test		
	Tensile strength N/mm²		Sampling position	vEo J	vTrs °C
B	963	No crack	WM	88	−88
Center	1 003	No crack	Bond	99	−78
F	972	No crack	HAZ	218	<−140
Mean	979	—	—	—	—

Notes 1) B : Backing side, F : Final side
2) WM : Weld metal, HAZ : Heat affected zone

5. Fracture Safety Assessment of Bifurcation

5.1 Brittle Fracture Arrestability of Base Metal

As shown in **Table 3**, values lower than −80°C were obtained for vTrs, thus satisfying the toughness requirement (≤ −60°C). Based on these values, the brittle fracture arrestability of base metal using WES3003 A-use criteria are shown in **Table 5**. The material therefore satisfies WES3003 A-use criteria at minimum service temperature, and it is suitable for use as sickle plate.

Table 5 Brittle fracture arrestability of base metal[8)]

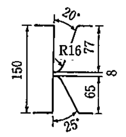
Required characteristics	Characteristics of developed steel	
Required Kca value	Kca value at 0°C	Minimum temperature required to retain required Kca value
6.433 kN/mm$^{3/2}$ at 0°C	≧13.7 kN/mm$^{3/2}$	≦−27°C

Note) Calculated in accordance with WES3003 (1983) A-use criteria

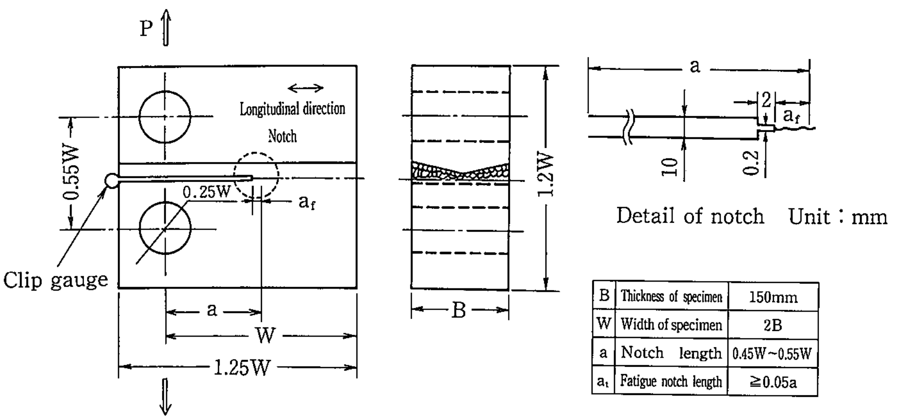
5.2 Brittle Fracture Initiation of Welded Joint

It was proved that charpy absorbed energy of each sampling position was of higher level than the value of target properties established in chapter 2.5. It was also proved that the CTOD value calculated from vE_0 and the critical CTOD value given in **Table 6**, which was obtained by the full thickness CT test of the welded joint shown in **Fig. 9**, were of a higher level than the required CTOD value determined in chapter 2.5. This means the material possesses sufficient capability of preventing brittle fracture initiation.

Table 6 Brittle fracture toughness test results of welded joint

Shape of groove	Compact tension test			
 Welding method : SAW	Testing temperature °C	Notch length a mm	Kc value kN/mm$^{3/2}$	Critical CTOD value $\delta_0$mm
	0	168.4	5.686	0.170
	0	189.0	5.801	0.219

Notch position : Fusion line at straight side



B	Thickness of specimen	150mm
W	Width of specimen	2B
a	Notch length	0.45W~0.55W
a_f	Fatigue notch length	≧0.05a

Fig. 9 Configuration of compact tension specimen

6. Advantages of HT980 in Comparison with HT780

6.1 Advantages of HT980

General effects of HT980's higher strength are shown in **Table 7.** Particularly in large scale pumped storage stations with large capacity and high water head, substantial reductions in wall thickness and, consequently, savings in construction cost are expected by utilising HT980 along with the rock-participation technique, which was employed in the design of penstock for Okumino power station (with HT780)[8].

Table 7 Advantages of HT980[8]

Item	Primary effect	Secondary effect
Design	Thickness reduction	Increase in rock participation rate and reduction of thickness
Erection	Weight reduction Reduction of weld deposit volume	Reduction of temporary facilities Reduction of construction period

6.2 Design of Bifurcation

Desing of bifurcation stands on realising the harmony of strength and hydraulic behaviour of the structure, as conceptually illustrated on **Fig.10.** It is often the case with materials of lower strength, that technical limitations caused by the necessary size of components force the balance point to lye in the design with bulky shape and thick dimensions, which is disadvantageous in the hydraulic point of view. Materials of higher strength, as is the case for HT980, can surmount these problems by shifting the balance point towards hydraulically desirable side[8].

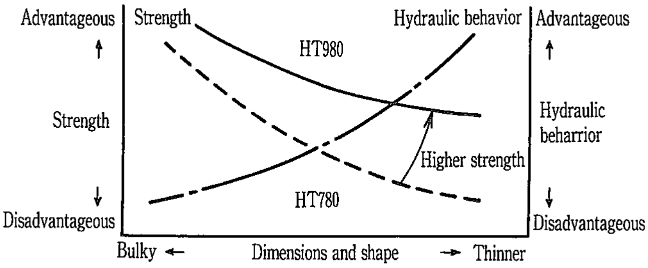


Fig. 10 Concept for design of bifurcation (Harmony of structural and hydraulic behavior)

6.3 Welding

The welding condition employed for the tests of welded joint of HT980 are shown in **Table** 8 in comparison with those for HT780. Since the results of the tests satisfied the all target properties under these conditions, it can be concluded that the developed steel has the same weldability as that of HT780.

Table 8 Comparison of welding conditions (Sickle plate)[8]

Item		HT980Z	HT780Z
Thickness	—	150mm	200mm
Ceq	—	0.66	0.59
Pcm	—	0.34	0.28
Preheating and interpass temperature	SMAW	150～200°C	150～230°C
	SAW	125～175°C	150～230°C
Condition of post heating	—	150°C x min. 2 hrs.	150°C x min. 2 hrs.
Heat input	—	≦4kJ/mm	≦5kJ/mm Average≦4.5 kJ/mm
Control of electrode	Drying condition	400°C x min. 1 hr.	350°C x min. 1 hr.
	Storage condition	150°C	150°C
Control of flux	Type	Bonded type	Fused type
	Drying condition	300°C× min. 1hr.	250°C x min. 1 hr.
	Storage condition	125°C	150°C

6.4 Cost Comparison with HT780

Although the unit price of steel plate rises for HT980, the weight of the steel plate decreases, resulting in total cost of materials may be roughly the same. HT980 may be used as a substitute for HT780 in order to reduce wall thickness and to save construction costs, transportation costs and construction period[8].

7. Conclusion

Developed 150mm thick HT980Z steel plate exhibits excellent base metal properties even for heavy thickness steel plate and satisfies target properties such as weldability, properties of welded joint, and properties of fracture toughness. These results also prove the sufficient fracture safety with 150mm thick HT980Z used as sickle plate of the Escher Wyss-type bifurcation.

Concerning the advantages of using HT980 for penstock, the developed 150mm thick HT980Z can be regarded as the most suitable material not only from the aspect of structural design, but also from the aspect of cost.

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