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Development of Ultraheavy-Gauge (210 mm Thick) 800 N/mm^2 Tensile Strength Plate Steel for Racks of Jack-up Rigs

Kozaburo Otani[*1]
Keiichi Hattori[*2]
Hirohide Muraoka[*2]
Humihiro Kawazoe[*2]
Sanae Tsuruta[*3]

Abstract:

Nippon Steel Corporation has developed a 210-mm thick plate steel, the world's heaviest-gauge material, for racks of jack-up rigs operating in frigid and very deep seas. The new ultraheavy-gauge steel combines a tensile strength of 800 N/mm^2 with excellent weldability and high notch toughness at the plate mid-thickness at −60°C. It is manufactured by optimizing the chemical composition and employing the latest steelmaking technology and advanced rolling, instead of forging, process.

1. Introduction

Offshore oil drilling rigs come in various types. The jack-up rig illustrated in **Fig. 1** is the most popular type. The racks of jack-up rig legs are mostly made of high-strength steel plates (HT80) with a strength of 780 to 870 N/mm^2 for weight reduction. The rack steel is required to have lamellar tearing resistance and gas cutability in addition to weldability and notch toughness.

Nippon Steel started work on the research and development of rack steel more than 10 years ago, and has manufactured rack steels for use in various marine environments and reported the results of their application achieved since then[1,2]. These high-strength steels ranged from 127 to 195 mm in thickness.

Recently, jack-up rigs are built of heavier-gauae steel plates for installation in deeper and more frigid seas, as **Fig. 2** indicates. In line with this trend of the times, Nippon Steel has developed a rack steel of the world's heaviest gauge of 210 mm with superior toughness. A rack gas-cut from the newly developed ultraheavy-gauge steel is shown in **Photo 1**, and legs having chords welded to such racks are shown in **Photo 2**.

This report describes the concept of development, manufacturing conditions, mechanical properties, and weldability of the

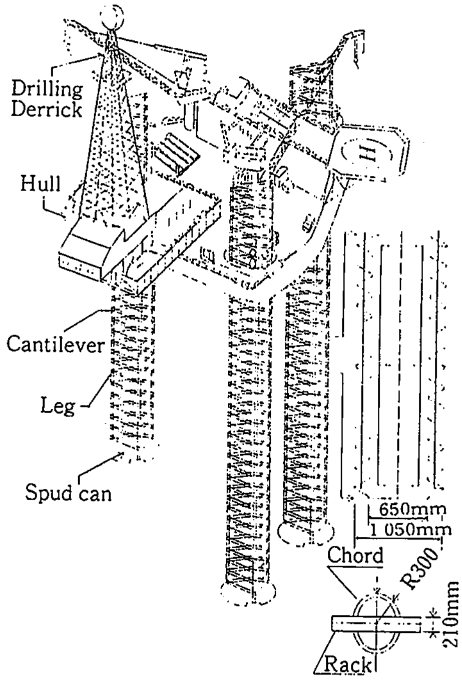


Fig. 1 Jack-up type rig

[*1] Technical Administration Bureau

[*2] Nagoya Works

[*3] Plant & Machinery Division

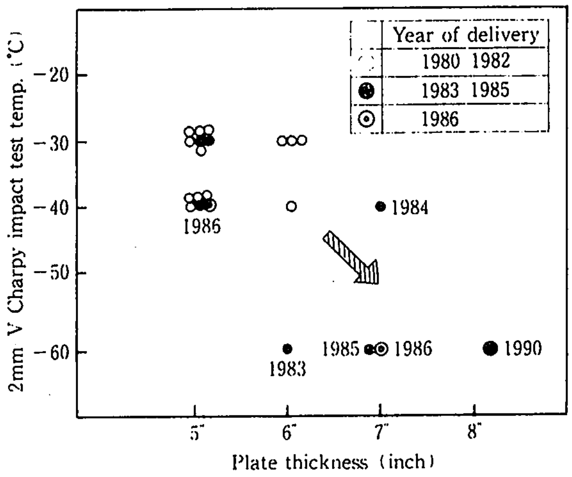


Fig. 2 Trend of order acceptance for rack plate steels

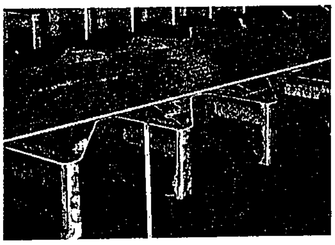


Photo 1 Appearance of rack gas cut from ultraheavy-gauge steel plate

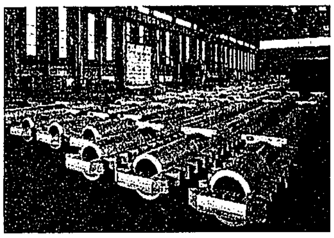


Photo 2 Appearance of legs using ultraheavy-gauge racks

new ultraheavy-gauge high-strength steel for low temperature service.

2. Alloying Design

2.1 Conventional way of thinking about chemical composition

Nippon Steel manufactured ultraheavy-gauge rack steel plates with thickness of 127 to 195 mm and tensile strength of 780 to 870 N/mm^2.

The basic findings regarding the alloying design of the rack plate steels are already reported[1,2] and may be summarized here as follows:

(1) The carbon content should be as low as possible to improve the fusion line toughness of welded joints.

(2) As the silicon content increases in the range of 0.1 to 0.4%, the tensile strength increases but the toughness of the steel decreases. Therefore, the silicon content must be held under 0.3%.

(3) The fusion line toughness of welded joints can be effectively increased by lowering the phosphorus content, and it remarkably improves when the phosphorus content falls under 0.008%.

(4) Boron is effective in improving the hardenability of the mid-thickness portion that is slow to cool, ensuring the uniformity of mechanical properties across the plate thickness.

(5) Increasing the nickel content is effective in improving low-temperature toughness and increasing tensile strength.

(6) Increasing the manganese, molybdenum, and nickel contents is effective in increasing the ideal critical diameter (DI) while keeping the carbon equivalent (Ceq) constant.

2.2 Development targets and determination of chemical composition

Table 1 compares the aimed chemical composition of the new HT 80 steel with those of conventional HT80 steels. The conventional HT80 steels guaranteed the specified toughness at the quarter-thickness of the plate at a Charpy impact test temperature of −60°C or above and measured up to 195 mm in thickness. The development targets of the new HT80 steel were the heavier gauge of 210 mm and the guarantee of ${}_{v}E_{-60^{\circ}C} \geqq 45$ J at the mid-thickness that makes it more difficult to guarantee the specified toughness than the quarter-thickness.

Fig. 3 shows the relationship between ${}_{v}E_{-60^{\circ}C}$ and 50% FATT (fracture appearance transition temperature at 50% shear) in HT80 steels. To guarantee ${}_{v}E_{-60^{\circ}C} \geqq 45$ J, the 50% FATT must be lowered to −55°C or less.

Fig. 4 shows the results of a Charpy impact test conducted to see if this requirement can be met with the 180 mm thick 1.9% Ni steel and 195 mm thick 2.5% Ni steel that are greater in thickness than conventional HT80 steels. The 210 mm thick HT80 steel

Table 1 Chemical composition of conventional ultraheavy-gauge HT80 steels and target chemical composition of new ultraheavy-gauge HT80 steel

Steel	Case (Thickness:mm)	Chemical composition (wt %)														Ceq (%)		*3 P_{CM} (%)	*4 DI (inch)	Remarks
		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	Al	B	N	JIS*1	IIW*2			
Conventional steel	1.9Ni (180)	0.12	0.32	1.07	0.006	0.002	0.28	1.85	0.51	0.56	tr	0.04	0.062	0.0012	0.0038	0.60	0.66	0.30	8.69	Guarantee of quarter-thickness ${}_{v}E_{-60^{\circ}C}$
	2.5Ni (195)	0.11	0.26	1.11	0.003	tr	0.24	2.46	0.70	0.51	tr	0.04	0.072	0.0012	0.0045	0.64	0.72	0.31	10.59	Guarantee of quarter-thickness ${}_{v}E_{-50^{\circ}C}$
Newly developed steel	Target (210)	0.11	0.25	1.05	≦0.005	≦0.001	0.25	3.35	0.70	0.55	—	0.04	0.065	0.0013	≦0.0060	0.64	0.78	0.32	12.15	

*1 Ceq (JIS) $= C + Si/24 + Mn/6 + Ni/40 + Mo/4 + V/14$

*2 Ceq (IIW) $= C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5$

*3 P_{CM} $= C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$

*4 DI $= 0.367\sqrt{C}(1 + 0.7Si)(1 + 3.33Mn)(1 + 0.35Cu)(1 + 0.36Ni)(1 + 2.16Cr)(1 + 3.0Mo)(1 + 1.75V)(1 + 1.77Al)$

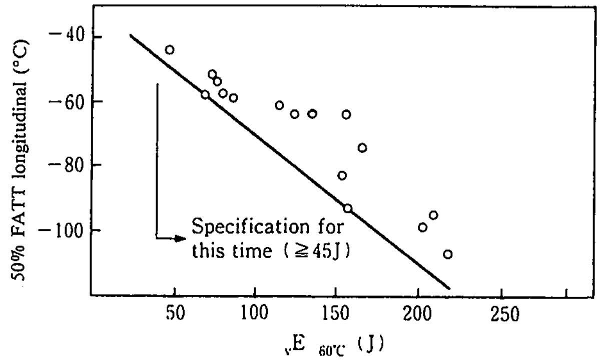


Fig. 3 Relationship between $_vE_{-60°C}$ and 50% FATT of HT80 steels

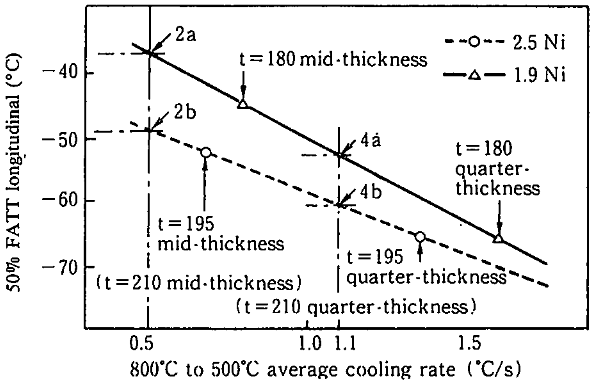


Fig. 4 Relationship between cooling rate and toughness of HT80 steels at mid-thickness and quarter thickness of plate

Table 2 Estimated toughness at center of 210 mm plate thickness for conventional and new chemical composition systems

Composition system	50% FATT (°C)
1.9Ni	−37
2.5Ni	−49
Target value	≦ −55

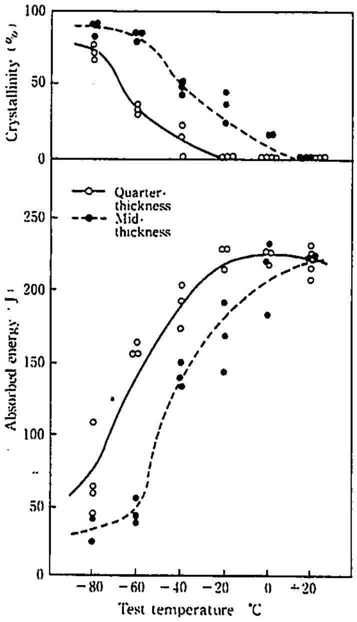


Fig. 5 Charpy transition curves (in rolling direction) of 1.9% Ni HT80 steel with thickness of 180 mm

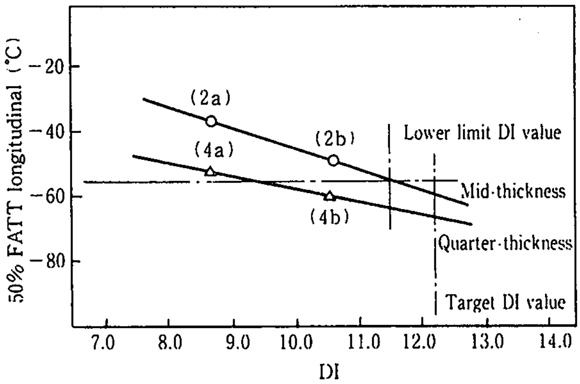


Fig. 6 Estimated DI value and toughness of 210 mm thick HT80 steel

was cooled at a rate of 0.5°C/s from 800 to 500°C at the mid-thickness on roller quench equipment. The 50% FATT at the mid-thickness of the 210 mm thick HT80 steel is estimated at the point 2a from the composition of the 180 mm 1.9% Ni steel and at 2b from the composition of the 195 mm thick 2.5% Ni steel. Similarly, the 50% FATT at the quarter-thickness of the 210 mm thick HT80 steel is estimated at the points 4a and 4b from the respective compositions. The estimated values of the 50% FATT are summarized in **Table 2**. When a conventional composition system is applied to the 210 mm thick HT80 steel that is slower to cool, the specified toughness becomes difficult to guarantee. When the mid-thickness of the 210 mm thick HT80 steel is cooled at a lower rate, upper bainite forms to degrade the toughness of the steel. To prevent the upper bainite formation, the hardenability (DI value) of the steel must be improved.

For reference, **Fig. 5** gives the Charpy transition curves of the 180 mm thick 1.9% Ni steel.

The DI value is generally related closely to the toughness of the steel. In **Fig. 6**, the 50% FATT values of the 210 mm thick HT80 steel (2a, 2b, 4a, 4b) as estimated from **Fig. 4** are related to the DI values of the above-mentioned 1.9% Ni and 2.5% Ni steels. It is evident from the figure that the DI value must be at least 11.5 to meet the requirement of 50% FATT ≦ −55°C at the plate mid-thickness. Therefore, the DI value was set at 12.1 for the new HT80 steel, considering the manufacturing variations. This DI value adjustment was made by increasing the amount of nickel that is effective in improving the matrix toughness of the plate, instead of changing the contents of such hardenability elements as carbon, manganese, chromium and molybdenum that affect weldability from their levels in the conventional HT80 steels. As a result, the nickel content of the new HT80 steel was calculated to be 3.35%.

In **Fig. 7**, the 50% FATT values of the 210 mm thick HT80 steel estimated from **Fig. 4** (2a, 2b, 4a, 4b) are related to the nickel contents of the above-mentioned 1.9% Ni and 2.5% Ni steels. If the nickel content is 3.35%, the 50% FATT is about −65°C, which fully satisfies the requirement of 50% FATT ≦ −55°C.

3. Manufacturing Conditions

3.1 Steelmaking process

A general manufacturing process for the new HT80 steel is shown in **Fig. 8**. The following steelmaking techniques are re-

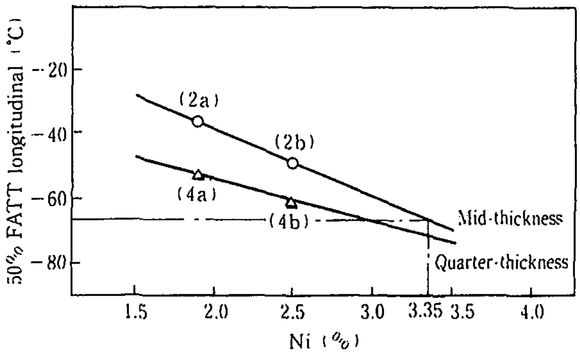


Fig. 7 Estimated necessary nickel content of 210 mm thick HT80 steel

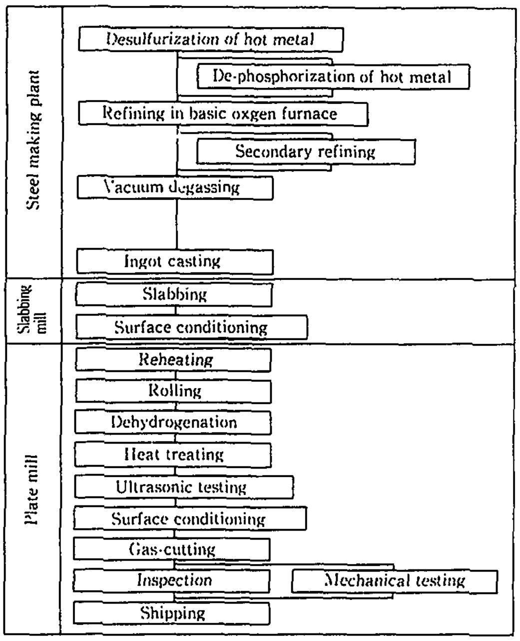


Fig. 8 Manufacturing process

quired for the manufacture of the steel:

(1) Control of nonmetallic inclusions to provide sufficient resistance to cracking during gas cutting and lamellar tearing in service (reduction in sulfur and oxygen contents)
(2) Control of internal flaws that increase with increasing plate thickness (reduction in hydrogen content)
(3) Reduction of phosphorus content and accomplishment of blowing end-point composition to provide the base metal and heat-affected zone of welded joints with a high level of toughness

Application with optimum conditions of hot metal pretreatment, secondary refining and vacuum degassing are important to achieve the above objectives. **Fig. 9** illustrates the high-cleanliness steelmaking process specifically developed to this end[3,4]. The new process can easily produce ultraclean steel with P $\leqq$ 0.005%, S $\leqq$ 0.001%, O $\leqq$ 15 ppm, and H $\leqq$ 1.5 ppm.

3.2 Rolling process

Generally in the rolling of a ultraheavy-gauge plate the reduction force applied to the mid-thickness of the plate is too weak to completely weld shut the voids formed in the solidification process. This problem was solved by the high-shape factor (contact length/average thickness) rolling technique that Nakao and his coworkers developed[5]. Their research results are shown in **Figs. 10 and 11**. As is evident from the two figures, the voids at the mid-thickness of the plate can be fully welded by increasing the shape factor to 1.0 or more by increasing the roll diameter and the reduction taken per pass. The high-shape factor rolling process also improves the gas cutability of the plate.

3.3 Heat treatment process

The thermal cycle from the heating of the slab through the quenching and tempering of the rolled plate is as shown in **Fig. 12**. The basic concept in determining the thermal cycle is based on the research results of Yamaba et al[2]. That is to say, the thermal cycle was determined from the point of view of the effective utilization of boron to impart the desired hardenability and the control of AlN precipitation.

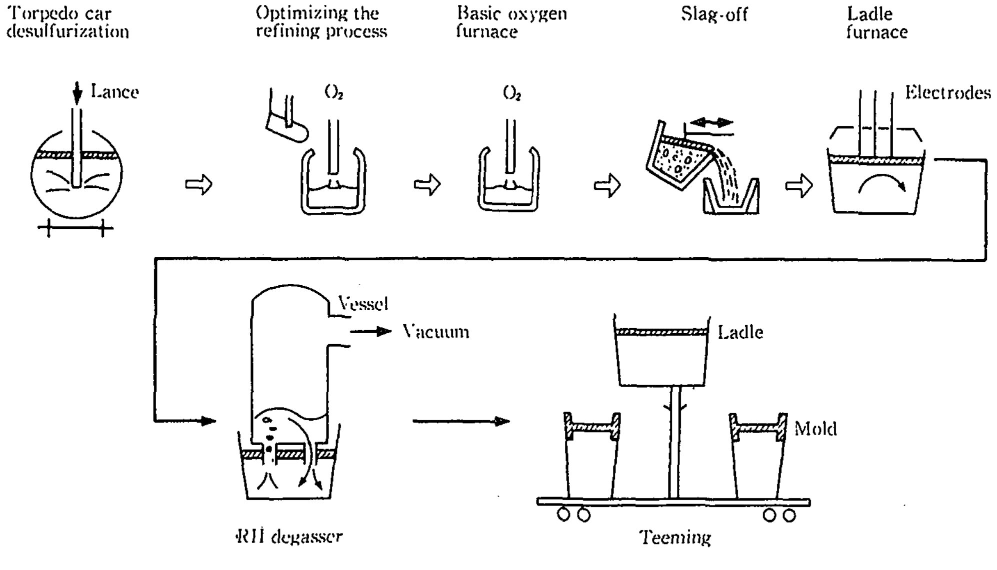
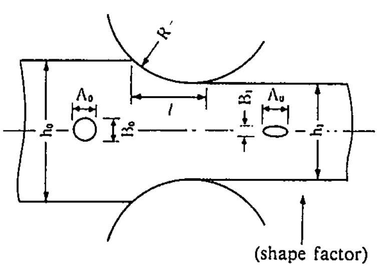


Fig. 9 High-cleanliness steelmaking process



$$\frac{l}{h_m} = \frac{\sqrt{R(h_0 - h_1)}}{1/2(h_0 + h_1)}$$

$$X = \frac{B_0 - B_1}{B_0} = 1 - \frac{B_1}{B_0}$$ (Deformation ratio of void in through thickness direction)

$$Y = \frac{A_0 - A_1}{A_0} = 1 - \frac{A_1}{A_0}$$ (Deformation ratio of void in rolling direction)

Fig. 10 Schematic illustration of shape factor l/hm, X and Y

To raise hardenability through the use of boron, boron needs to be prevented from forming boron nitride (BN) and be in the state of free boron before quenching. This requirement can be effectively met by fixing nitrogen in the condition of aluminum nitride (AlN). In this case, aluminum is added slightly in excess. AlN precipitates coarsely on cooling after slabbing and degrades the low-temperature toughness of the base plate. Therefore, the slab must be heated at 1,200°C or above so that coarse AlN can be completely dissolved in the form of aluminum and nitrogen. For AlN to be precipitated finely in the plate being heated during quenching, the T_1 temperature (cooling temperature after rolling) must be controlled at 400°C or lower.

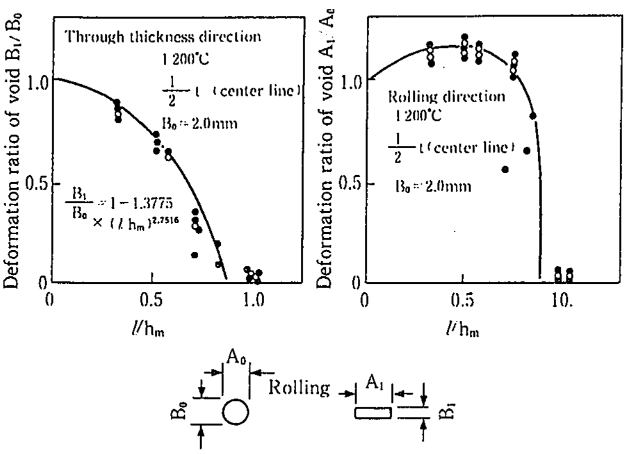


Fig. 11 Effect of shape factor on deformation ratios B_1/B_0 and A_1/A_0

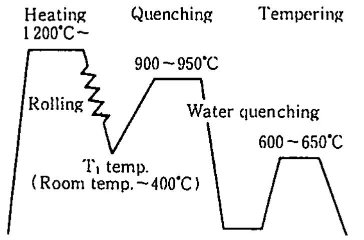


Fig. 12 Heat cycle of quenching and tempering

Table 3 Chemical composition of new HT80 steel (wt%)

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Al	B	N	Ceq (JIS) (%)	Ceq (IIW) (%)	P_{CM}	DI (inch)
Target	0.11	0.25	1.05	≦0.005	≦0.001	0.25	3.35	0.70	0.55	0.04	0.065	0.0013	≦0.0060	0.64	0.78	0.32	12.1
Typical example	0.11	0.24	1.06	0.003	0.001	0.24	3.30	0.69	0.54	0.03	0.078	0.0014	0.0045	0.65	0.78	0.32	11.9

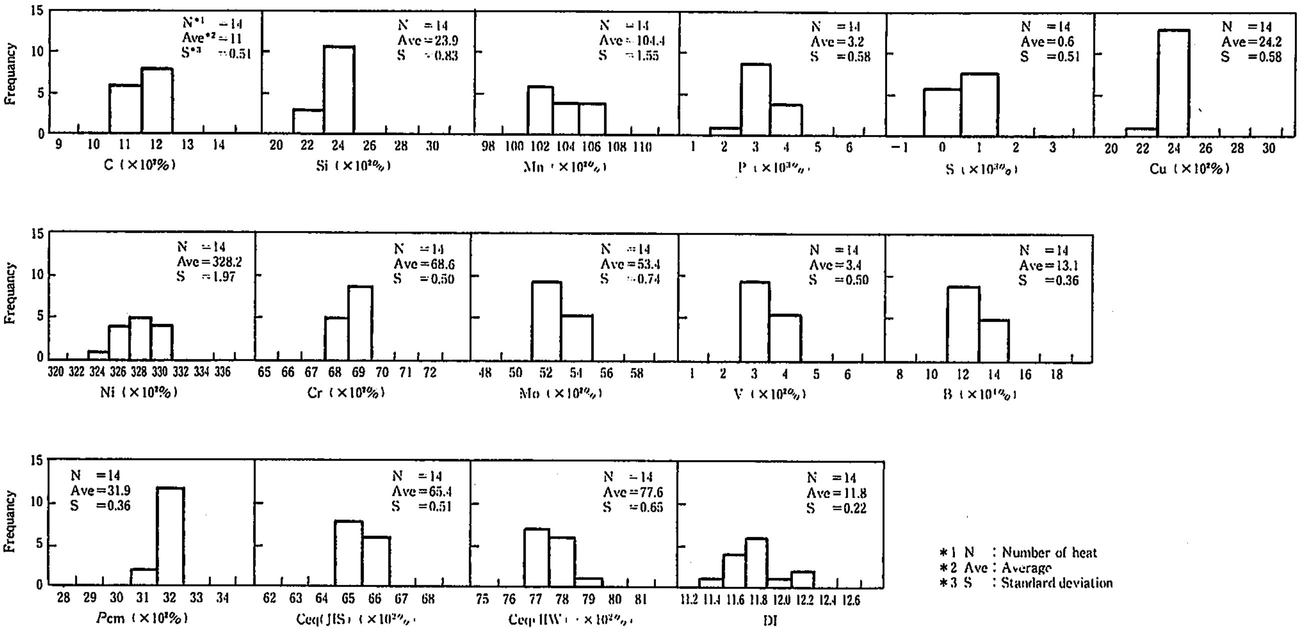


Fig. 13 Results of chemical analysis of heat

4. Manufacturing Results

Described below are the results of the new HT80 steel manufacture on a production line according to the alloying design and manufacturing conditions described above.

4.1 Chemical composition

Table 3 compares the actual chemical composition of the new HT80 steel with its target values. As seen, the actual values are generally the same as the target values. **Fig. 13** gives more detailed results of chemical analysis. Each alloying element is extremely small in variability, and such impurity elements as phosphorus and sulfur are held extremely low, thanks to the high-cleanliness steelmaking technology.

4.2 Mechanical properties

The tensile and bend test results of the base plate are as shown in **Table 4**. The tensile strength is higher than the target value of 834 N/mm^2, and the bend test result is satisfactory, too.

Fig 14 shows the Charpy impact test results. The 50% FATT is lower than the target value of −55°C, and the absorbed energy at −60°C is more than three times the target value of 45 J.

The hardness distribution across the plate thickness is as shown in **Fig. 15**. The difference of hardness between the center and surface is small despite the large plate thickness. This attests to the sufficient hardenability effect of boron.

5. Weldability

5.1 Y-groove weld cracking test

The new HT80 steel was weld cracking tested according to JIS Z 3158. The specimens had the plate reduced in thickness by 50 mm on one surface, as shown in **Fig. 16**. **Fig. 17** shows the test results. When preheated to 150°C, weld cracking was prevented from occurring, demonstrating weldability comparable to that of the conventional HT80 steel.

5.2 Maximum hardness test

The maximum hardness test of the new HT80 steel was con-

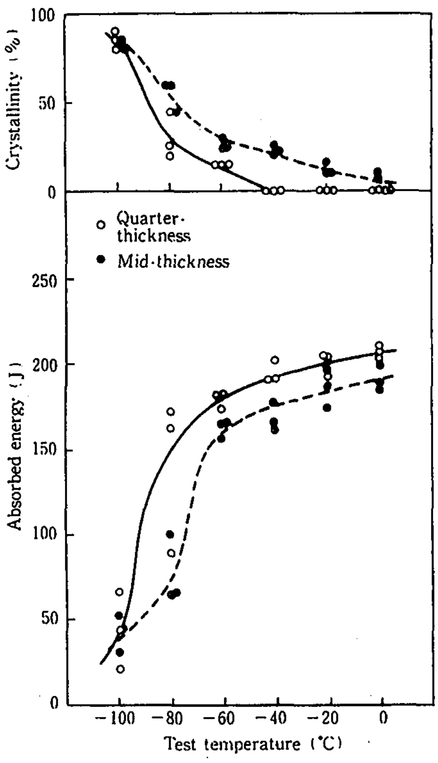


Fig. 14 Results of 2-mm V-notch Charpy impact test (rolling direction)

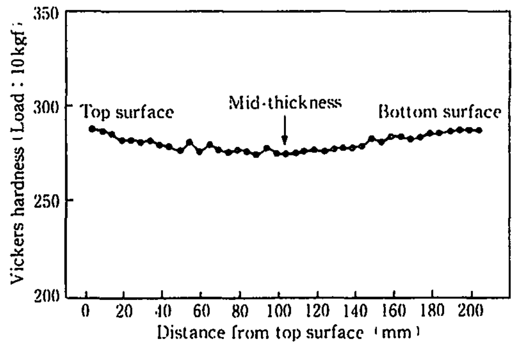


Fig. 15 Hardness distribution in thickness direction

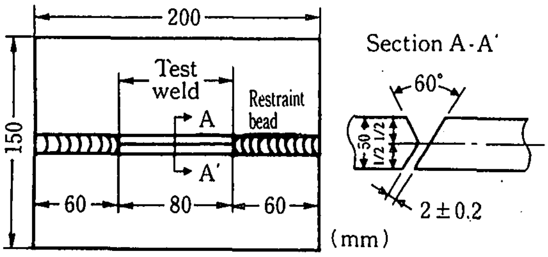


Fig. 16 Geometry of y-groove restraint cracking test specimen

Table 4 Results of tensile and bend tests (transverse to the rolling direction)

Heat No.	Plate thickness (mm)	Heat treatment	Thickness position	Tensile test				Bend test		
				Yield point (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Reduction area (%)	Radius	Angle	Result
NQ0477	210	Quenched and tempered	1/4-thickness	826 827	886 884	19 20	64 65	Twice of thickness	180°	Good
			1/2-thickness	786 789	854 859	20 20	66 65			Good
Target	210	Quenched and tempered	1/4-thickness	Minimum 686 ($\geqq$70kgf/mm^2)	Minimum 834 ($\geqq$85kgf/mm^2)	Minimum 15	—	Twice of thickness	180°	No cracking

Note: (1) Tensile test specimen: Round type (Gauge length = 70mm, diameter = 14mm)
(2) Bend test specimen: Reduced to 35mm, thickness with the original top surface retained

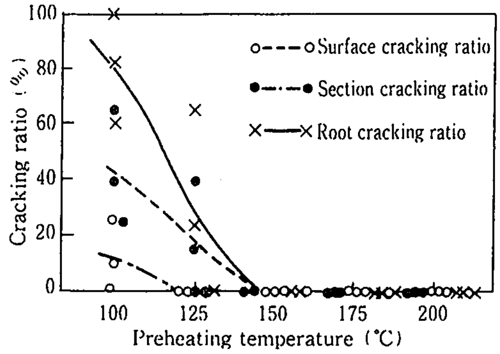


Fig. 17 Results of y-groove restraint cracking test

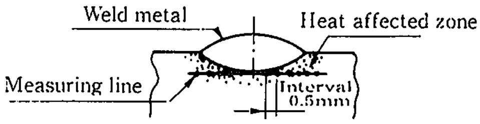


Fig. 18 Hardness test method

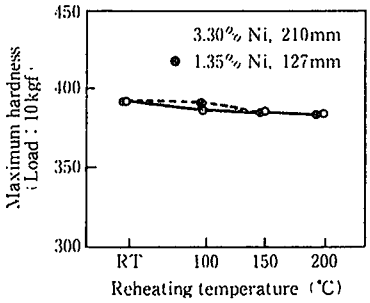


Fig. 19 Results of maximum hardness test

ducted in conformance with JIS Z 3101, as shown in **Fig. 18**. **Fig. 19** compares the maximum hardness of the new HT80 steel with the conventional 127 mm thick HT80 steel. The new HT80 steel exhibits approximately the same Vickers hardness (under the load of 10 kgf) as the 127 mm thick HT80 steel. The Vickers hardness of the new HT80 steel hardly changed between 385 and 392 from room temperature to the preheating temperature of 200°C.

6. Performance of Welded Joints

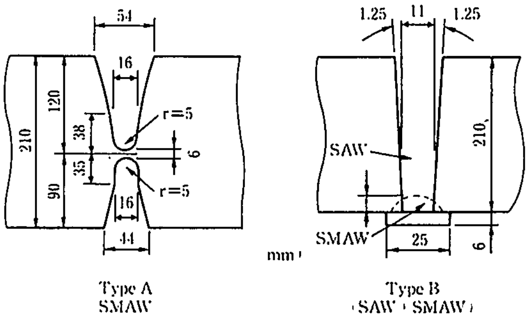
To investigate its welded joint performance, the new HT80 steel was welded by shielded metal arc welding (SMAW) and submerged arc welding (SAW), two processes most frequently used for welding racks of jack-up rigs, and tested. The welding conditions are as listed in **Table 5**, and the groove shapes are as illustrated in **Fig. 20**. These conditions are generally applied to the welding of rack steels with tensile strength of 780 to 870 N/mm^2.

6.1 Tensile test of welded joints

The tensile test results of welded joints are as shown in **Table 6**. Three tensile test specimens were taken from each welded joint in the thickness direction owing to the capacity of the testing machine employed. The tensile test specimens are of the same geometry as that of welded joint tensile test specimens specified by Lloyd's Register of Shipping. All the test specimens marked higher than the target value of 834 N/mm^2.

Table 5 Welding conditions for welded joint test

Groove shape	Type A	Type B	
Welding method	SMAW	SAW	SMAW
Welding consumables	L-80SN (4.5mmϕ)	Y-80M × NB250H (3.2mmϕ)	L-80SN (4.5mmϕ)
Welding current (A)	130-180	470-500	170-230
Arc voltage (V)	23-25	28-30	25
Travel speed (cm/min)	7-12	29-32	18-24
Heat input (kJ/mm)	1.6-2.8	2.7-3.0	1.3-1.7
Preheating temperature (°C)	100	100	130
Interpass temperature (°C)	105-130	96-130	110-130



Type A
SMAW

Type B
(SAW + SMAW)

Fig. 20 Groove shapes

Table 6 Tensile test results of welded joints

Type	Thickness location	Test piece size (mm)		Tensil strength (N/mm^2)	Fractured location
		Thickness	Width		
A (SMAW)	Surface to 1/3-thickness	69.90	25.10	896	Weld metal
		69.70	25.10	890	Weld metal
	1/3-thickness to 2/3-thickness	70.05	25.10	925	Weld metal
		70.00	25.00	916	Weld metal
	2/3-thickness to thickness	70.10	25.10	925	Weld metal
		70.00	25.10	913	Weld metal
B (SAW + SMAW)	Surface to 1/3-thickness	70.10	25.10	938	Base metal
		69.70	25.10	941	Base metal
	1/3-thickness to 2/3-thickness	70.00	25.10	937	Base metal
		70.00	25.15	943	Base metal
	2/3-thickness to thickness	70.15	25.15	938	Base metal
		70.10	25.15	944	Base metal

6.2 Charpy impact test of welded joints

Three Charpy impact test specimens were taken from each welded joint in the thickness direction, as shown in **Fig. 21**. The notch was machined at the center of the weld metal (WM), in the fusion line (FL), and at 2 mm from the fusion line (FL + 2 mm). The test results are as shown in **Table 7**. The absorbed energy at the test temperature of −60°C is higher than the target value of 45 J in the FL and FL + 2 mm notch locations where the influence of the base metal is high.

7. Conclusions

Nippon Steel has developed a new HT80 steel with tensile strength of 780 to 870 N/mm^2 and the world's heaviest gauge of 210 mm for racks of the legs of jack-up rigs, employing the special rolling process that it developed in place of the expensive

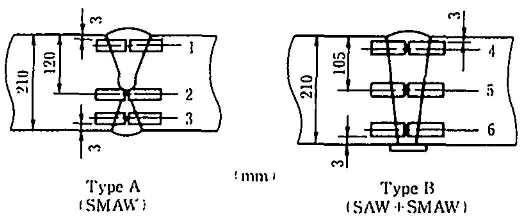


Fig. 21 Locations of Charpy test piece sampling

Table 7 Results of 2-mm V-notch Charpy impact test of welded joints

Type	Thickness location (See Fig. 21)	Notch location	Test temp. (°C)	Absorbed energy (J)			
				Each value			Ave. value
A (SMAW)	1	WM	−60	77	91	86	85
		FL	−60	201	221	196	206
		FL+2mm	−60	206	231	142	193
	2	WM	−60	67	62	73	67
		FL	−60	157	93	142	131
		FL+2mm	−60	201	238	160	200
	3	WM	−60	96	142	82	107
		FL	−60	109	75	86	90
		FL+2mm	−60	98	211	211	173
B (SAW + SMAW)	4	WM	−60	69	75	84	76
		FL	−60	128	95	155	126
		FL+2mm	−60	219	192	211	207
	5	WM	−60	60	54	52	55
		FL	−60	234	196	179	203
		FL+2mm	−60	93	150	62	102
	6	WM	−60	64	69	64	66
		FL	−60	91	167	69	109
		FL+2mm	−60	241	211	172	208

forging process.

The new HT80 steel has approximately the same weldability as conventional ultraheavy-gauge HT80 steels despite its heavier gauge. It also guarantees the toughness specified for the mid-thickness of the plate where the desired toughness is most difficult to achieve at the test temperature of −60°C. The new HT80 steel is manufactured by optimizing chemical composition, applying heat treatment, adopting the high-cleanliness steelmaking process, and employing the high-shape factor rolling process.

The features of the new HT80 steel follow:

(1) The 2-mm V-notch Charpy absorbed energy ${}_{v}E_{-60^{\circ}C}$ at the mid-thickness of the base plate is higher than 45 J, and the fracture appearance transition temperature at 50% shear (50% FATT) is lower than −55°C.

(2) The 2-mm V-notch Charpy absorbed energy in the heat-affected zone of welded joints fully satisfies the requirement of ${}_{v}E_{-60^{\circ}C} \geqq 45$ J and is at the same level as that of the base metal.

(3) The weldability of the new HT80 steel is comparable to that of conventional ultraheavy-gauge HT80 steels for low-temperature-service jack up-type rig racks, and the necessary preheating temperature in the y-groove weld cracking test is 150°C.

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