KAWASAKI STEEL TECHNICAL REPORT
No.6 (September 1982)

Making and Fabricating of Steel Components for Jack-up Rig Legs

Keinosuke Hamada, Toshiaki Wake, Yuji Kusuhara, Yasue Koyama, Katsuaki Nakatsuji

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Kawasaki Steel's 80 kgf/mm² high-strength plates are widely used in the fabrication of legs for jack-up rigs to build the lightweight and yet strong offshore structures. This paper introduces various features of Kawasaki Steel's plates and other products used for the rigs, including seamless pipes. It also outlines the process of manufacture and fabrication of various components of the legs. Special welding jigs were devised to meet critical design specifications for welded structures, and careful quality control was performed by setting up important check points.

1 Introduction

The demand for rigs for offshore oil field development has now become slightly stagnant, but during the period from late 1979 to early 1981, offshore oil-drilling rigs enjoyed a worldwide boom; in particular, nearly 100 jack-up rigs were constructed during the period[1], accounting for about 50% of the total number of jack-up rigs constructed during the past 30 years. The jack-up rig is primarily of the stationary type fixed on the sea bottom of less than 100 m in depth, and a great number of high strength steels are used for the leg which forms the jacking system. Kawasaki Steel Corporation has for the past several years been not only supplying steels for legs but also accepting orders for leg fabrication. This report reviews the supply of steels and fabrication of jack-up rigs on the basis of the above-mentioned records.

2 Problems in Construction and Fabrication of Legs

Legs are broadly divided into a comparatively simpler cylindrical shape and a lattice structure as shown in **Fig. 1**. In this report, only the latter type will be described because a great number of high strength steels are used for racks, chords and braces, and there are also many problems in their fabrication.

The ordinary practice on this leg is to drive the pinion equipped to the jack frame for elevating and descending the leg continuously. The leg is composed of the rack, chord, and brace, and there are many shapes of racks and chords as shown in **Fig. 2**. The rack is frequently made of 80 kgf/mm² class high strength steels of 125 to 150 mm in thickness and the chord employs various grades of high strength steels including 80 kgf/mm² class. Since the coupling portion of the rack and chord is formed by welded joints of heavy-plate construction, it poses many problems. Namely, while high efficiency is required from the viewpoint of weldability, there is a risk of deformation of members and lowering of mechanical properties of the weld, thereby requiring careful welding control. In order to support 3 or 4 chords equipped to a single leg, seamless pipes of various grades of high strength steel of 200 to 300 mm in outside diameter are used. At the joints of the braces, groove shapes peculiar to pipe constructions are used, and complete penetration welding is predominantly used. Since manual welding at high ground working places is frequently employed, the welders must also be highly skilled.

Besides welding, leg fabrication also involves a problem of very strict dimensional accuracy in fabrication. It is important, therefore, to understand fully the mutual relationship between these matters, in order to fabricate the leg. The following report is given on steels, welding materials and fabrication records concerning the fabrication of the leg from the viewpoints mentioned above.

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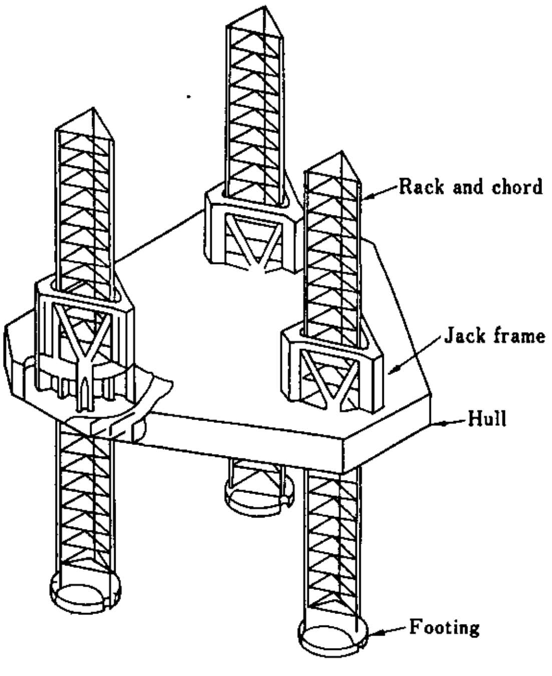


Fig. 1 Outline of legs and jack frame

3 Steels and Welding Materials for Leg

3.1 Heavy Section Steel Plates of 80 kgf/mm² Class for Rack

The rack must have excellent Z-direction (through-thickness direction) properties and low temperature toughness against high heat-input welding in view of its construction and welding as shown in **Fig. 2**. The properties of rack materials which meet such requirements are described below.

3.1.1 Fundamental principles of quality design

For rack materials, ASTM standard A514 Series is applicable, and **RIVER ACE** 80 and 80M correspond to the series. In the following, the fundamental concept of the quality planning is described.

(1) Al, B, and N contents

The optimum contents of Al, B, and N for necessary strength and toughness of base metal were clarified by Funakoshi et al.[2] With reference to these test results, the effects of B and N contents on the weld bond toughness were inspected by the synthetic heat-affected zone test. The results are shown in **Figs. 3** and **4**. On the basis of the test results, B and N contents are suppressed to the minimum.

(2) Ni content

The Ni content is effective in enhancing the toughness of base metal and the weld, but since it is costly, an excessive addition of Ni raises unnecessarily the production cost of steel materials. **Fig. 5** shows the results of the weld bond toughness improving effects by Ni addition under various welding conditions by the synthetic heat affected zone test. The content of Ni addition is mainly determined by the required levels of the plate thickness and toughness of the base metal, taking into consideration the toughness of the weld. **Table 1** shows the target values of Ni content, and Kawasaki Steel is producing heavy section steel plates within the Ni ranges shown in the table.

(3) Carbon Equivalent (C_{eq}) and Weld Cracking Sensitivity (P_{CM})

The structure in which the toughness of 80 kgf/mm² class high strength steel shows the best value is the one which can be made by tempering the mixture of martensite and a small quantity of lower bainite. In order to obtain such a structure, the target C_{eq} is determined according to the plate thickness, but taking into consideration the weld cracking sensitivity, the values of C_{eq} and P_{CM} are suppressed to the barest minimum. The crack arresting temperatures in the "y" groove restrain cracking test of 100 mm thick heavy section steel plate were satisfactorily low as shown in **Fig. 6**.

(4) Internal Quality

Internal defects of heavy section steel plates frequently originate in hydrogen in steel or the loose structure. Therefore, vacuum degassing of molten steel, high reduction during rolling (the pass schedule with a rolling shape factor* of more

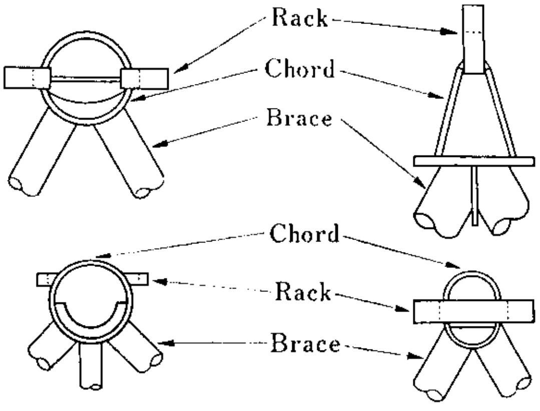
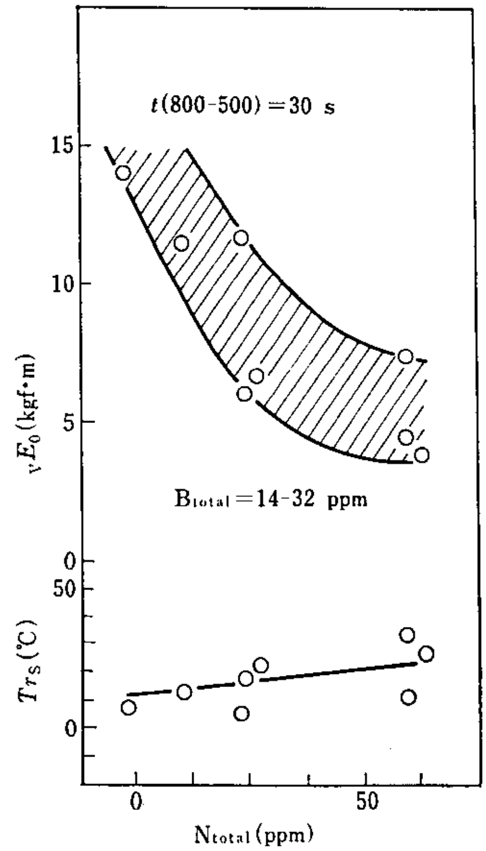


Fig. 2 Typical sections of racks and chords

$$*\text{S.F.} = \frac{2\sqrt{R(H_i+H_{i+1})}}{H_i+H_{i+1}}$$

H_i: Plate thickness at the ith pass

R: Roll radius



t(800 500) : Cooling time from 800 to 500°C

Fig. 3 Effect of N content on Charpy impact properties of simulated weld bond

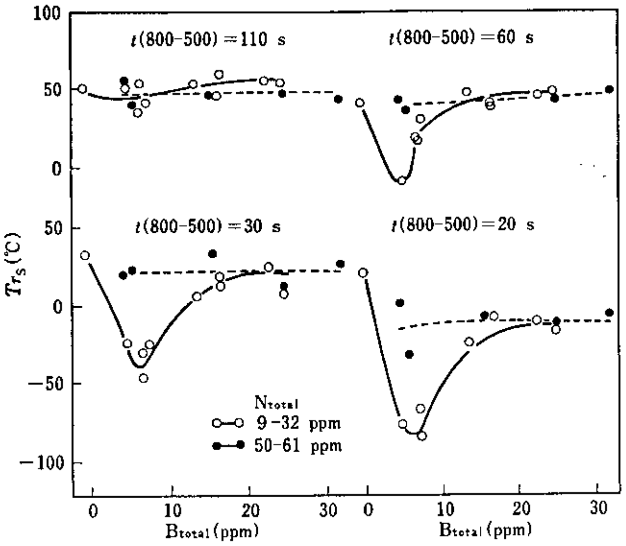
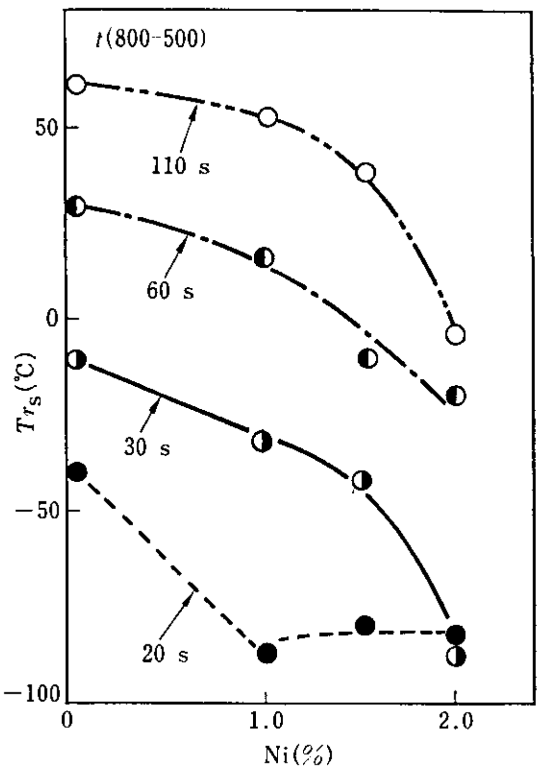


Fig. 4 Effect of B content on Charpy impact properties of simulated weld bond



Chemical composition (%)

C	Si	Mn	Cr	Mo
0.10	0.25	0.80	0.50	0.50

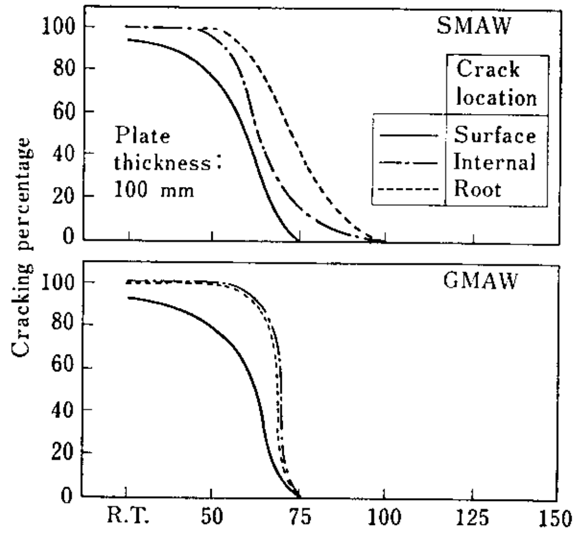
Cu	V	Al	N	B
0.25	0.03	0.06	0.002 5	0.000 6

Fig. 5 Effect of Ni content on Charpy impact properties of simulated weld bond

Table 1 Preferable range of Ni content for 80 kgf/mm² heavy plate

Thickness (mm)	Test temperature (°C)		
	−30	−40	−50
127 (5")	Low	Low or medium	Medium or high
152 (6")	Medium		
178 (7")and over	High		

Low : Ni≦0.5%
Medium : 0.5%<Ni≦1.0%
High : 1.0%<Ni



1) Welding conditions

SMAW

Electrode	KS-116
Core dia.	ϕ 4 mm
Amperes	170 A
Volts	24 V
Heat input	16 kJ/cm

GMAW

Wire	KM-80
Wire dia.	ϕ1.6 mm
Shielded gas	Ar16+$CO_2$4 l/min
Ampepes r	320 A
Volts	32 V
Heat inpvtu	29 kJ/cm

2) Chemical composition of plate

C	Si	Mn	P	S	Cu	Ni
0.15	0.28	0.80	0.007	0.006	0.24	1.24

Cr	Mo	V	B	C_{eq}	P_{CM}
0.47	0.52	0.033	0.0015	0.55	0.30

Fig. 6 Results of y-groove restraint cracking test

than 0.5 in each pass), and slow cooling after rolling are essential.

3.1.2 Example of quality characteristics

An example of rack material which has been produced on the basis of the above-mentioned quality planning is reviewed below. **Tables 2** and **3** show chemical compositions and mechanical properties of medium-Ni 80 kgf/mm² class high strength steel plates (plate thickness: 140 mm). **Fig. 7** also shows the results of Charpy impact test on the plate-thickness center of butt-welded joints by MIG and submerged arc welding. The figure indicates that both base metal and weld had excellent strength and toughness within the temperature range of −30 to −40°C.

High Ni 80 kgf/mm² class steel plates (thickness:

Table 2 An example of chemical comppsition of medium-Ni 80 kgf/mm² heavy plate, 140 mm thick

(%)

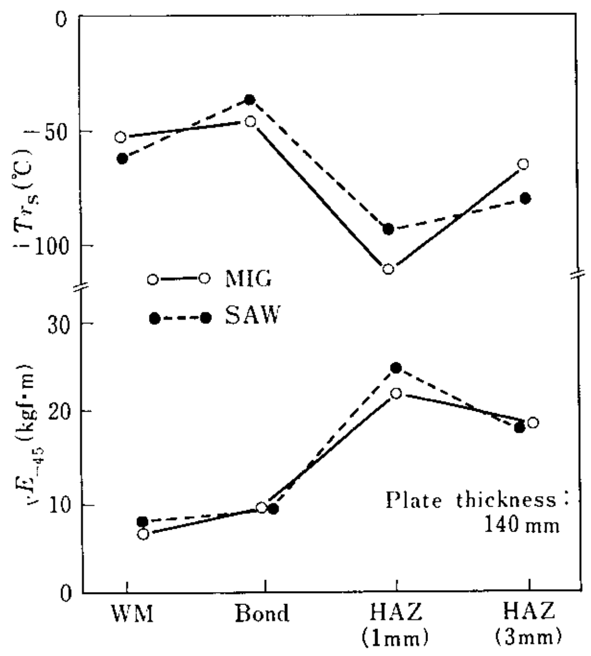
C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Al	B	N	$C_{eq.}$	P_{CM}
0.12	0.24	0.90	0.009	0.005	0.25	0.90	0.58	0.45	0.04	0.051	0.001 4	0.003 7	0.534	0.271

$C_{eq.}=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14$

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

Table 3 Tensile and Charpy impact properties of the plate shown in Table 2

Position	Direction	P.S. (0.2%) (kgf/mm²)	T.S. (kgf/mm²)	El. (%)	R.A. (%)	vE_{-20} (kgf·m)	vE_{-45} (kgf·m)	vE_{-60} (kgf·m)	vT_S (℃)	Tr_{30} (℃)
1/4 *t*	L	73.4	80.9	25	71	22.9	21.5	18.8	−67	<−80
	T	74.7	82.1	22	67	19.3	14.4	7.0	−51	<−80
1/2 *t*	L	70.9	80.5	23	69	16.1	5.0	3.7	−24	−52
	T	72.7	81.4	22	63	6.9	3.8	2.7	−4	−40



	MIG	SAW
Welding material	KM-80T	KW-103B × KB-80C
Heat input (kJ/cm)	21.9–24.6	28.8–40.8

Fig. 7 Charpy impact properties of welded joint of medium-Ni 80 kgf/mm² heavy plate

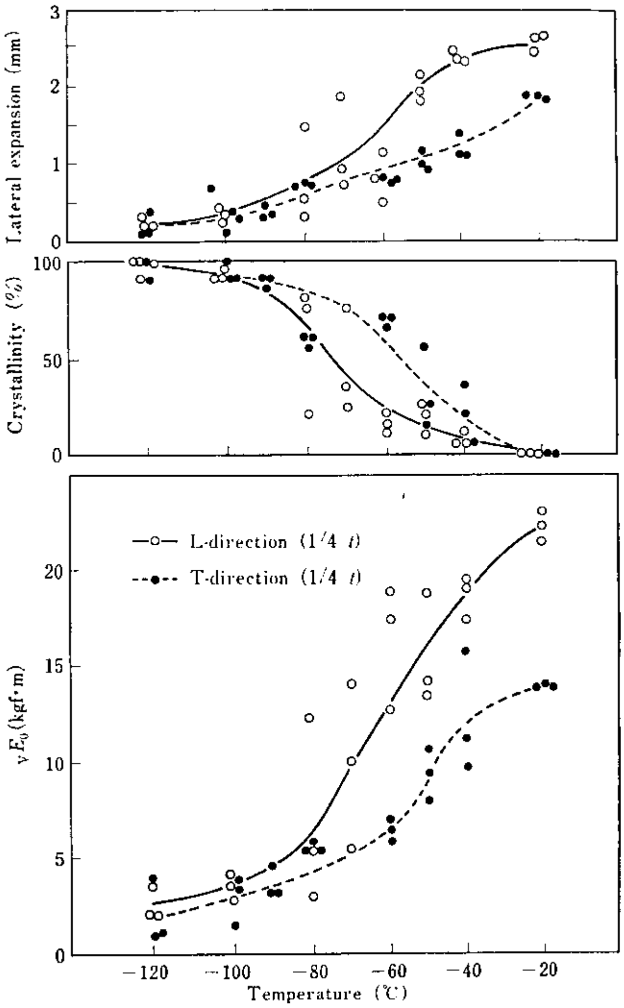


Fig. 8 Charpy transition curves of high-Ni 80 kgf/mm² heavy plate

Table 4 An example of chemical composition of high-Ni-80 kgf/mm² heavy plate, 150 mm thick

(%)

		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	Al	C_{eq}	P_{CM}
Ladle		0.15	0.26	1.02	0.017	0.003	0.26	1.40	0.71	0.55	0.047	0.001 1	0.056	0.55	0.32
Check	1/4 t	0.14	0.27	1.02	0.015	0.003	0.24	1.39	0.72	0.56	0.047	0.001 1	0.054	0.54	0.31
	1/2 t	0.14	0.27	1.03	0.016	0.003	0.24	1.40	0.72	0.57	0.048	0.001 0	0.056	0.54	0.31

Table 5 Tensile and Charpy impact properties of the plate shown in Table 4

Position	Direction	P.S.(0.2%) (kgf/mm²)	T. S (kgf/mm²)	El. (%)	R.A. (%)	$_vE_{-60}$ (kgf·m)	Tr_E (℃)	Tr_S (℃)
1/4 t	L	76.3 76.3	84.3 84.6	26 27	74 74	16.4	−66	−74
	T	76.8 76.3	84.3 84.3	24 23	67 65	6.5	−58	−57
1/2 t	L	75.9 75.7	84.9 84.0	26 26	70 72	3.2	−42	−44
	T	75.9 75.9	84.6 84.6	23 26	61 61	4.1	−45	−47

150 mm) were used to investigate their various characteristics including the low-temperature toughness of the base metal. **Tables 4** and **5** show their chemical compositions and mechanical properties, respectively. To investigate their toughness, they were submitted to a 2-mm V notch Charpy impact test, and an example of the transition curve is shown in **Fig. 8**. The steel plates were also submitted to the COD test by 3-point bending and the drop weight test. The results of the respective tests are shown in **Figs. 9** and **10**. The value of δ_C shown in **Fig. 9** was obtained by BS standard 5762. **Fig. 11** shows the relation between the brittle fracture initiation temperature and the half length of a through-thickness crack which was obtained from the following equations **(1)** to **(3)** using the above-mentioned δ_C; this figure clearly indicates that the steel plates have excellent low-temperature toughness:

$$K_C = \sqrt{E \cdot \sigma_y \delta_C} \cdots\cdots\cdots\cdots\cdots\cdots \mathbf{(1)}$$

K_C: Fracture toughness value (kgf/mm$^{3/2}$)
E: Young's modulus (kgf/mm^2)
σ_y: Yield stress (kgf/mm^2)

$$K_C = 11\,892\exp(-542/T) \cdots\cdots\cdots\cdots \mathbf{(2)}$$

$$K_C = K_{IC} = \sigma\sqrt{\pi \cdot a} \cdots\cdots\cdots\cdots\cdots\cdots \mathbf{(3)}$$

a: Half length of a through-thickness crack (mm)
σ: Applied stress (kgf/mm^2)
T: Test temperature (°K)

3.1.3 Production record

The amount of 80 kgf/mm^2 class high-strength steel plates produced for jack-up rigs in the past two years exceeded 10 000 tons, and the heaviest-gage steel plate of them was the 216 mm thick ASTM A514F steel plate manufactured for the pinion.

An example of mechanical properties of the material in process is shown in **Table 6**.

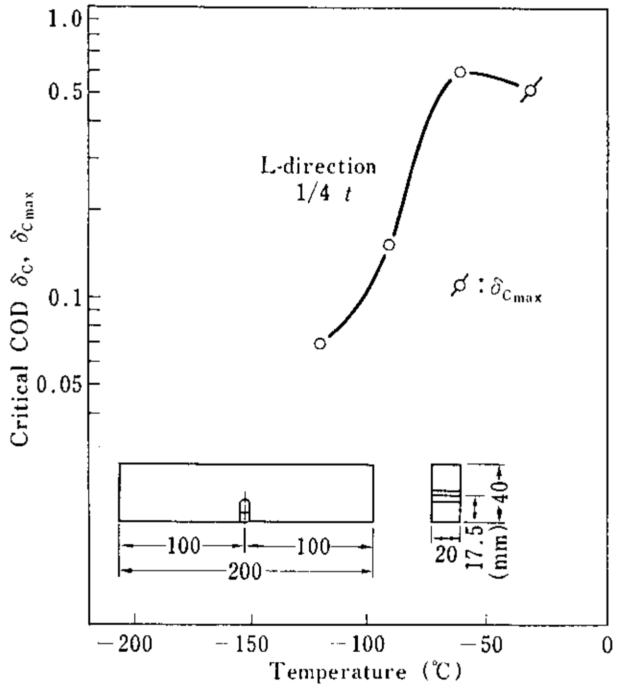


Fig. 9 Temperature dependence of critical COD of high-Ni 80 kgf/mm^2 heavy plate, 150 mm thick

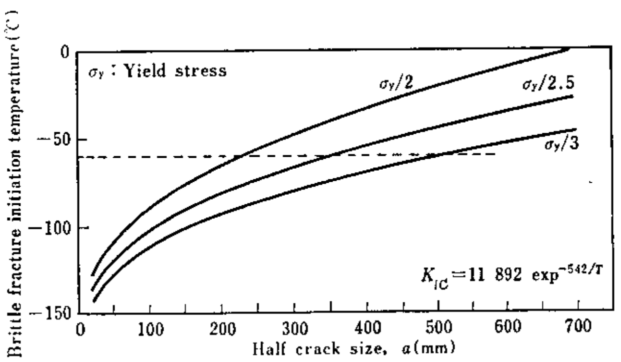
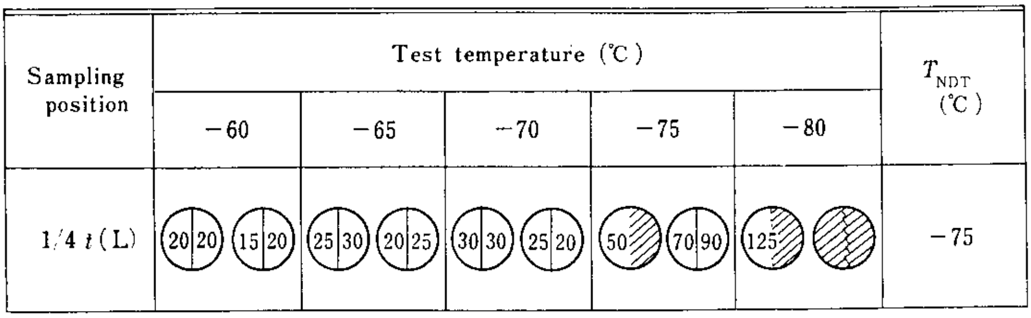


Fig. 11 Calculated relation between brittle fracture initiation temperature and half length of a through-thickness crack



Sampling position	Test temperature (℃)					T_{NDT} (℃)
	−60	−65	−70	−75	−80	
1/4 t (L)	20 20 15 20	25 30 20 25	30 30 25 20	50 ▨ 70 90	125 ▨ ▨	−75

Fig. 10 Nil-ductility transition temperature of high-Ni 80 kgf/mm^2 heavy plate, 150 mm thick

Table 6 Examples of tensile and Charpy impact properties of 80 kgf/mm² heavy plate used for rack

Thickness (mm)	T.S. (kgf/mm²)	T.S. (kgf/mm²)	El. (%)	$_{\mathrm{v}}E_{-50}$ (kgf·m)
127	69-79 〔72.7〕	75-85 〔79.7〕	21-27 〔24.0〕	9-21 〔14.6〕
152.4	67-77 〔69.9〕	75-83 〔78.0〕	22-27 〔25.1〕	9-21 〔14.9〕

〔 〕indicates the average.

3.2 Seamless Pipes

Seamless pipes made into brace materials cover wide ranges in tensile strength of 40 to 80 kgf/mm² and in wall thickness of 5 to 40 mm depending upon the locations of use, and thus various grades and sizes of pipes are used. Further, these seamless pipes are required to have high qualities such as excellent low-temperature toughness and weldability.

Table 7 Examples of chemical compositions of seamless pipes used for braces

(%)

Grade		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	Al	B	C_{eq}	P_{CM}
KHP 80	Spec.	Max. 0.16	0.15 0.35	0.50 1.30	Max. 0.030	Max. 0.010	0.10 0.50	0.20 1.20	0.10 0.80	0.10 0.06	–	0.020 0.080	–	Max. 0.003 5	Max. 0.60	–
	Ladle	0.12	0.25	0.87	0.013	0.005	0.18	0.79	0.62	0.38	–	0.044	0.095	0.002 8	0.52	0.27
	Check	0.11	0.25	0.86	0.014	0.004	0.19	0.83	0.63	0.38	–	0.044	0.094	0.002 6	0.51	0.26
KHP 60	Spec.	Max. 0.16	0.20 0.50	1.00 1.50	Max. 0.025	Max. 0.010	–	–	–	Max. 0.30	–	Max. 0.050	–	–	Max. 0.44	–
	Ladle	0.10	0.26	1.19	0.018	0.004	0.01	0.02	0.02	0.13	–	0.032	–	0.002 3	0.35	0.19
	Check	0.09	0.26	1.20	0.019	0.004	0.01	0.02	0.02	0.13	–	0.031	–	0.002 3	0.34	0.18
KHP 50	Spec.	Max. 0.18	Max. 0.35	0.90 1.60	Max. 0.025	Max. 0.010	–	–	–	–	Max. 0.05	Max. 0.05	Max. 0.05	–	–	–
	Ladle	0.15	0.28	1.27	0.016	0.003	0.01	0.01	0.01	<0.01	0.016	0.041	0.016	–	0.38	0.23
	Check	0.16	0.27	1.32	0.017	0.003	0.01	0.01	0.01	<0.01	0.018	0.040	0.018	–	0.40	0.24

Table 8 Specification of mechanical properties and dimension of seamless pipes for braces

Grade	Tensile test			Charpy impact test	Flattening test	Dimension tolerance
	Y.S. (kgf/mm²)	T.S. (kgf/mm²)	El. (%)	Absrobed energy* (kgf·m)		
KHP 80	Min. 70	80 95	Min. 18	$_{\mathrm{v}}E_{-30} \geqq 4.5(\bar{x})$ 3.5(any)	H $\leqq D(1.08-0.078D/t)$ D : Outside diameter t : Wall thickness	Outside diameter ±1 %N.O.D. Wall thickness ±12.5% N.W.T Straightness Max. 1 mm/1 000 mm Deviation in wall thickness Max. 15%
KHP 60	Min. 50	60 75	Min. 20	$_{\mathrm{v}}E_{-30} \geqq 4.5(\bar{x})$ 3.5(any)		
KHP 50	Min. 32	48 60	Min. 22	$_{\mathrm{v}}E_{0} \geqq 3.2$(any)		

* Full size (10×10)

Table 9 Tensile and Charpy impact properties of **KHP** 80, 60 and 50

Grade	Diameter (mm)	Thickness (mm)	Y.P. (kgf/mm²)	T.S. (kgf/mm²)	El. (%)	Test temp. (℃)	$_{\mathrm{v}}E_0$ $_{\mathrm{v}}E_{-30}$ (kgf·m)
KHP 80	298.5	16	86 88〔87〕	90-92〔91〕	33-36〔35〕	−30	14-20〔17〕
KHP 60	298.5	10	67-68〔68〕	70-72〔72〕	31-33〔32〕	−30	15-20〔18〕
KHP 50	165.2	6	37-39〔38〕	52-54〔53〕	37-40〔39〕	0	18 〔18〕

〔 〕 indicates average.

3.2.1 Mechanical properties and welded joint performance

Kawasaki Steel's Standards for seamless pipes which correspond to high strength steel having tensile strength of 80, 60 and 50 kgf/mm² are **KHP80**, 60 and 50, respectively. The chemical compositions and mechanical properties together with dimensional tolerances of these seamless pipes are shown in **Tables 7** and **8**, respectively.

In selecting the chemical compositions of the seamless pipes used, steels whose C_{eq} was suppressed to the minimum were adopted, taking weldability into consideration. **Table 9** shows the results of tensile and impact tests; **Fig. 12** shows the results measurements of the outside diameter, wall thickness, deviation in wall thickness, and straightness. Both figures indicate that these seamless pipes have sufficient strength and dimensional accuracy.

Next, the results of investigation of **KHP80** and 60 for their welded joint performance are explained. **Table 10** shows the results of testing the strength and toughness of joints under the welding conditions of butt welding of a groove angle 60°V with heat-input of 17 and 25 kJ/cm, respectively. This table indicates that **KHP80** and 60 have sufficient strength and toughness at both the heat-inputs.

Table 10 Mechanical properties of butt-welded joints of seamless pipes for braces

(a) Tensile strength

Grade	Heat input (kJ/cm)			
	17 kJ/cm		25 kJ/cm	
	T.S. (kgf/mm²)	Fractured position	T.S. (kgf/mm²)	Fractured position
KHP 80	90 85	W.M. W.M.	86 84	H.A.Z. W.M.
KHP 60	73 71	W.M. W.M.	70 69	W.M. W.M.

(b) Charpy absorbed energy

Grade	Notch position	Heat input	
		17 kJ/cm	25 kJ/cm
		$_vE_{-30}$ (kgf·m)	
KHP 80	Weld metal	6.5	5.0
	Bond	9.0	6.0
	H.A.Z. center	12.0	9.6
	Parent metal	16.0	16.2
KHP 60	Weld metal	8.2	7.0
	Bond	7.0	6.2
	H.A.Z. center	15.5	8.4
	Parent metal	22.0	21.3

3.2.2 Production method and capacity and material certification

Steels for **KHP80** and 60 are rolled from round billet into seamless pipes by the Mannesmann plug mill or mandrel mill and then given quenching, tempering and heat treatment. Heat treatment facilities are divided into ① the induction heating, or external water quenching method and ② the furnace heating, or external and internal water quenching method. In the external and internal quenching and tempering facilities, 80 kgf/mm² class high strength seamless pipes having a maximum diameter of 426 mm and a maximum wall thickness of 38 mm can be manufactured.

For pipe materials to be used for legs, **KHP80** and 60 have been given certification of Classification Societies such as NK, ABS, LR, BV, and NV, and **KHP50** has been given certification of NK and ABS.

3.3 Welding Materials

In the above sections, heavy section steel plates for racks and seamless pipes for braces have been described, but in welding them together, the selection of welding materials for 80 kgf/mm² class high strength steel and their properties must be considered.

3.3.1 Welding of KHP80

In the joint portion of **KHP80** and chord, the degree of restraint is great, so that cracking at the root pass (hot cracking and cold cracking starting therefrom) is liable to occur. To prevent this cracking, the following measures are effective:

(1) To minimize Ni content in the weld metal (hot cracking countermeasure)
(2) To minimize the content of diffusible hydrogen (cold cracking countermeasure)
(3) Under-matching weld is used for only the root pass

Taking these measures into consideration, the anti-hygroscopic low-hydrogen-based electrode **KSA-86** for 60 kgf/mm² class high strength steel was employed for root pass welding for **KHP80**.

As free from Ni addition, this electrode has excellent hot cracking resistance, but deterioration of its impact characteristics has to be compensated. After re-examining its chemical composition, excellent results have been obtained. The chemical composition and mechanical properties of deposited metals are shown in **Tables 11 to 13** and **Fig. 13**. As can be seen clearly from the figure, the impact properties of the

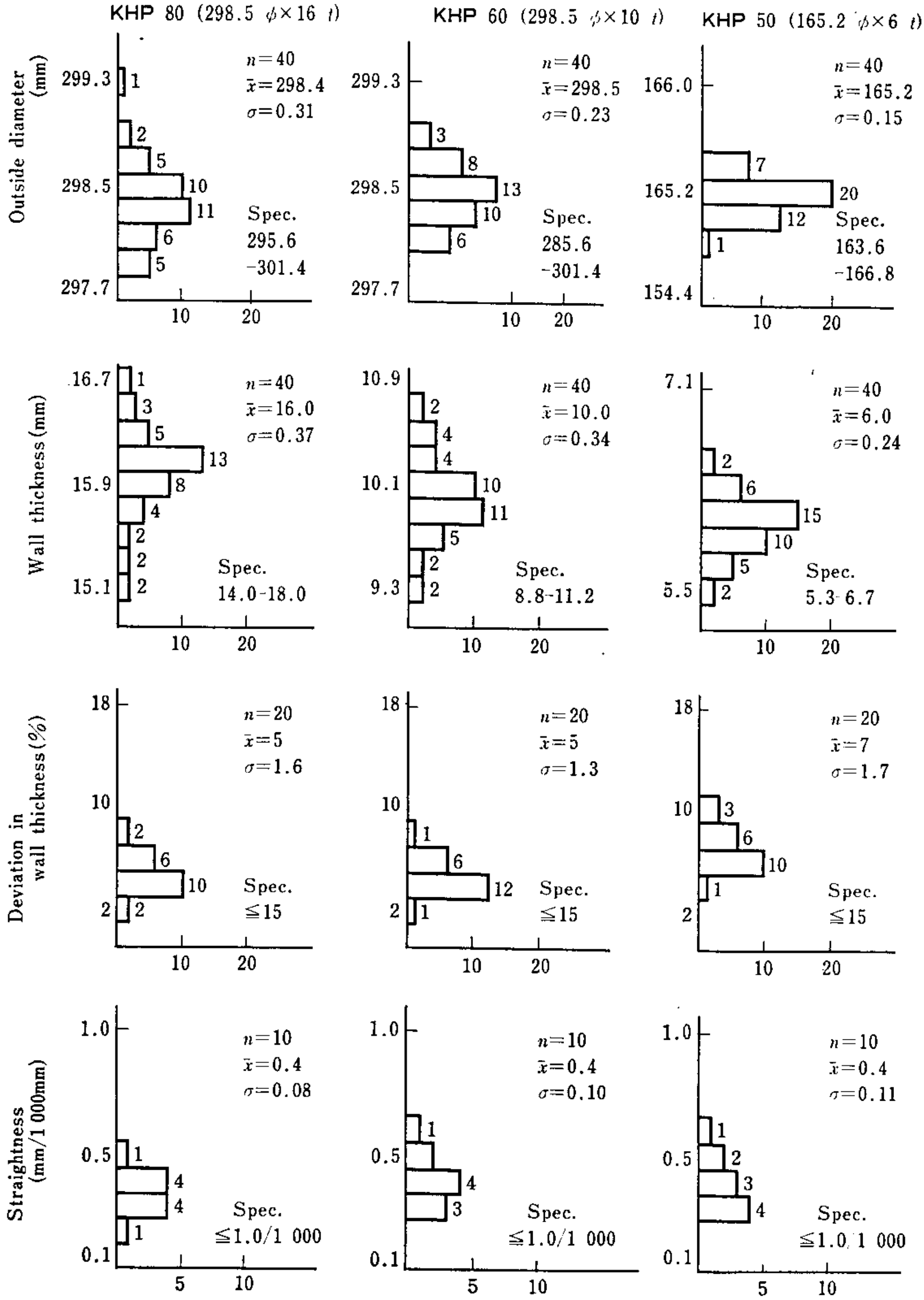


Fig. 12 Dimensional distribution of seamless pipes (KHP 80, 60 and 50)

Table 11 Chemical composition of all-deposited metal (%)

Electrode brand	C	Si	Mn	P	S	Ni	Mo	Ti	Al	O
KSA-86 (4 mmϕ)	0.07	0.40	1.33	0.013	0.008	<0.01	0.25	0.031	<0.005	0.034 6
KSA-86 (5 mmϕ)	0.07	0.41	1.35	0.014	0.008	<0.01	0.25	0.031	<0.005	0.034 3
KS-86H	0.07	0.66	1.15	0.014	0.013	0.60	0.25	0.031	0.006	0.039 0

Table 12 Tensile properties of all-deposited metal shown in Table 11 as **KSA-86**

Core dia. (Heat input)	Heat treatment	Y.P. (kgf/mm^2)	T.S. (kgf/mm^2)	El. (%)	R.A. (%)
4 mmϕ (18 kJ/cm)	AW	59.2	65.0	28	74
	SR	58.1	63.5	29	74
5 mmϕ (22 kJ/c m)	AW	59.6	65.5	31	75
	SR	57.3	63.8	31	76

AW : As weld

SR : Stress relieved at 600℃ for an hour

Table 13 Charpy absorbed energy of all-deposited metal shown in Table 11 as **KSA-86** (4 mmϕ)

Heat input (kJ/cm)	Heat treatment	$_vE_0$ (kgf·m)	$_vE_0$ (kgf·m)	$_vE_{-40}$ (kgf·m)
18	AW	22.4(10) 22.3(10) 21.5(10) 〔22.1(10)〕	15.8(25) 19.6(15) 19.4(20) 〔18.3(20)〕	14.7(30) 12.0(35) 13.6(30) 〔13.4(32)〕
	SR	24.3(10) 25.9(5) 22.0(10) 〔24.0(8)〕	20.7(15) 17.2(35) 22.2(15) 〔20.0(22)〕	6.0(60) 7.4(60) 11.8(35) 〔 8.4(52)〕
40	AW	20.7(25) 19.9(25) 24.2(5) 〔21.6(22)〕	20.1(25) 15.5(50) 20.2(25) 〔18.6(33)〕	11.7(55) 10.8(55) 14.9(45) 〔12.5(48)〕
	SR	24.9(10) 21.4(20) 24.9(10) 〔23.7(13)〕	19.7(20) 19.2(30) 23.4(20) 〔20.8(23))	10.3(55) 10.4(60) 13.3(55) 〔11.3(51)〕
·60	AW	21.9(15) 21.0(20) 22.2(15) 〔21.7(16)〕	20.3(25) 20.6(25) 22.1(20) 〔21.0(23)〕	9.7(60) 7.0(70) 4.7(70) 〔 7.1(67)〕
	SR	23.6(15) 18.1(20) 14.3(30) 〔18.7(22)〕	12.4(50) 8.5(60) 13.4(45) 〔11.4(52)〕	2.0(75) 2.6(75) 4.3(80) 〔 3.0(77)〕

( ) : Percentage of brittle fracture occurrence

〔 〕 : Average

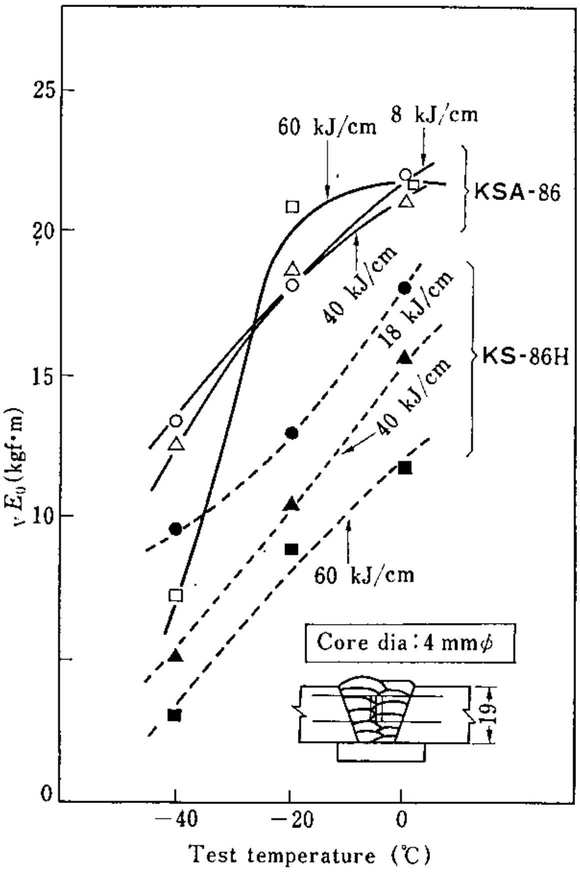


Fig. 13 Absorbed energy of all-deposited metal as weld
KSA-86: Ni bearing
KS-86H: Ni free

deposited metal by the Ni-free electrodes are better than those of Ni-based electrodes (**KS-86H**) at respective heat-inputs.

The diffusible hydrogen content in weld metal is affected by the atmosphere isolation conditions and the composition and absorption character of the covering of electrode. **KSA-86** has been made anti-hygroscopic by making the single flux in the covering anti-hygroscopic and by using lithium silicate as binder. Also, in order to reduce its porous surface area, high-temperature drying is applied to the elec-

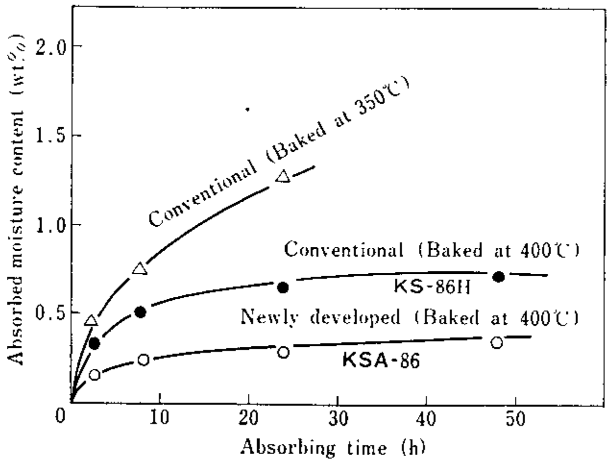


Fig. 14 Comparison of absorption characteristics of electrode coatings at 30°C and 80% humidity

Table 14 Minor effect of moisture absorption of KSA-86 electrode coating on hydrogen content of weld metal

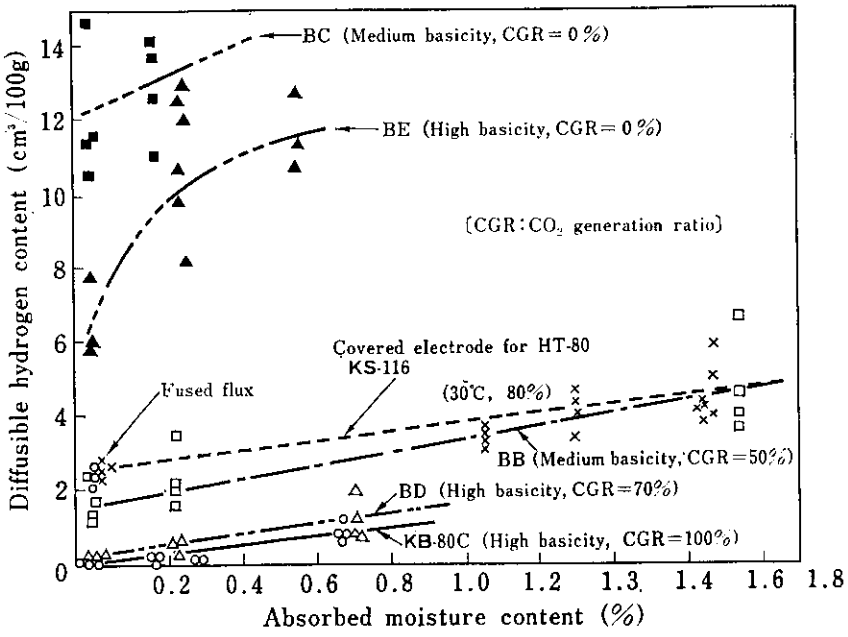
Moisture control	Diffusible hydrogen content (CC/100 g)	
	Each value	Average
As dried at 400℃ for an hour	0.9, 1.3, 0.6, 0.6 1.2, 1.3, 1.4, 1.2	1.1
Held for 24 h at 30℃ in 80% humidity after the above drying	2.0, 2.2, 2.0, 2.3	2.1

trode before the root pass welding. As a result, electrode control has become easier. **Fig. 14** shows that **KSA-86** has a lower absorption character than the conventional electrode. The diffusible hydrogen content of the weld metal is naturally very low immediately after drying and its addition is minimal even after **KSA-86** is left standing for a long period, as shown in **Table 14**.

3.3.2 Welding of rack and chord

Since the weld portion of rack and chord is large in wall thickness and length, the highly efficient submerged arc welding (SAW) method was adopted. At the time of SAW adoption, flux **KB-80C** and alloy wire **KW-103B** were selected as welding materials which are excellent in crack resistance and mechanical properties and capable of high heat-input welding.

The neutral flux **KB-80C** has high basicity and contains carbonates as shown in **Fig. 15**; thus its diffusible hydrogen content is minimal and its crack resistance excellent. Since the oxygen content in the weld metal is designed to be 250 ppm, excellent mechanical properties have been obtained and high heat-input welding is also possible. Mechanical properties of deposited metals through the combination of **KB-80C** and **KW-103B** are shown in **Tables 15** and **16** and **Fig. 16**, which clearly indicate that excellent impact properties can be obtained even at high heat-input.



$$\mathrm{CGR} = \frac{\text{Carbonate content in a flux}}{\text{Carbonate content in KB-80C flux}} \times 100(\%)$$

Fig. 15 Relation between absorbed moisture content and diffusible hydrogen content of weld metal

4 Fabrication of Leg

Structural portions of two identical type elevators for jack-up rigs Nos. 7 and 8 "HAKURYU" were ordered by Mitsubishi Heavy Industries and fabricated at Kawasaki Steel's Mizushima Works and Harima Fabrication Center during the period from June 1980 to October 1981.

In this paper the fabrication method of the legs shown in **Fig. 17** which were fabricated at Mizushima Works and its problems will be explained. Since it was necessary to clarify the welding method of 80 kgf/mm² class high strength steel and fabrication method to meet the strict requirements for dimensional accuracy to the welded structures, a full-sized model (a 9.5 m long regular triangle having a side in the cross section of 9.5 m) was trial-made and tested prior to actual fabrication. Through this test, the methods of gas-cutting the rack, assembling the rack and chord, and full assembling of the leg were established, before actual fabrication was commenced.

Table 15 Mechanical properties of all-deposited metal

(a) Chemical composition (%)

C	Si	Mn	P	S	Ni	Cr	Mo
0.04	0.32	1.44	0.011	0.005	2.64	0.64	0.47

(b) Tensile and Charpy impact properties

Y.P. (kgf/mm²)	T.S. (kgf/mm²)	El. (%)	R.A. (%)	vE_0 (kgf·m)	vE_{-20} (kgf·m)
70.6	83.4	24*	65	15.3	13.0

*G.L.=50 mm

4.1 Gas-cutting of Rack

The rack is located at the three-vertex portion of the leg and is an important component which is engaged with the pinion equipped to the jack frame, thereby elevating the leg; and therefore, its finishing accuracy is considerably strict as shown in **Fig. 17.** For gas-cutting the rack, a numerical control automatic gas cutter is used. Since the plate thickness is as large as 125 mm and the steel is of the 80 kgf/mm² class high strength, many preliminary cutting tests were conducted.

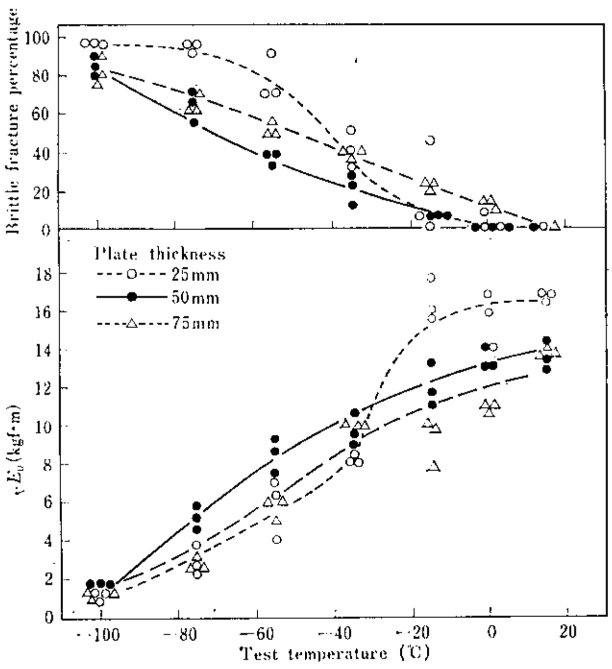
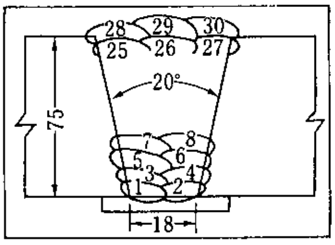


Fig. 16 Charpy impact characteristics of welded joint

Table 16 Welding condition and test result of welded joint

Groove shape and build-up sequence	Welding condition							Joint tensile test		Side bend test	
	Pass No.	Amp. (A)	Volt. (V)	Speed (cm/min)	Heat input (J/cm)	Preheat. temp. (°C)	Interpass temp. (°C)	T.S. (kgf/mm²)	Break down position	Crack formation	Bending angle
	1 | 30	600	30	22	49 000	100	149 | 159	82.3 83.7	M.M M.M	Nothing Nothing	Over 180°

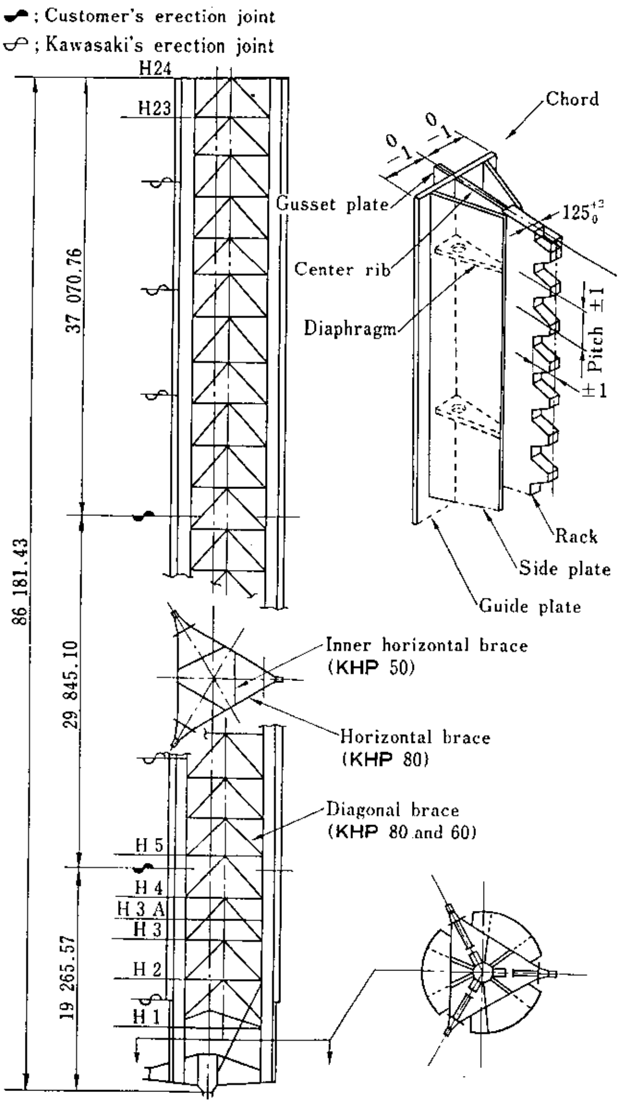


Fig. 17 Leg outline

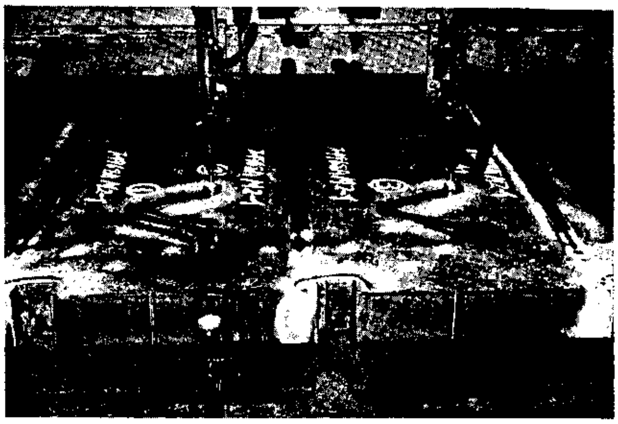


Photo 1 Rack cutting

In the following, an outline is given concerning the method of restraint of members with the jig, gas cutting procedure, gas cutting conditions (types of nozzles, cutting speed, oxygen and gas pressure, etc.) and distortion straightening method is given below.

Depending upon the plate width, 4 to 6 racks were cut from a single plate. In order to forestall the possible elongation of the entire steel plate by the heat input and the resultant deviation of cutting positions, one end of the steel plate was fixed securely to the cutting stand by welding, and the other end of the steel plate was left free from any support. Both sides of the steel plate were provided with stoppers.

After various examinations on the cutting procedure it was decided to cut the straight-line portion and gear teeth in this order, then the steel was temporarily cooled and the remaining portion of the steel plate was cut off.

In the cutting conditions, it was unavoidable to sacrifice efficiency to a certain extent in order to meet the strict quality requirements such as the hardness of teeth, surface roughness, squareness of teeth, etc. The divergent nozzle was used, and cutting speed was set to 120 to 150 mm/min. Oxygen pressure was set at 3.5 to 4.0 $\mathrm{kgf/cm^2}$, and gas pressure for preheating flames at 0.2 to 0.3 $\mathrm{kgf/cm^2}$. The cutting was performed at nighttime during which crane traveling was rare, because vibration during gas cutting would cause notch generation. **Photo 1** shows the gas-cutting condition of the rack. Owing to the side-gear rack, non-uniform heat input and a difference in heat input between the nozzle side and anti-nozzle side occurred, resulting in bending and warping of 5 to 10 mm per 10 m in length of the steel plate; thus press straightening was performed. The push-in quantity and push-in position were also given careful attention, because cracking was liable to occur during press straightening. After press straightening, all the test pieces were checked on the centering surface table. The results were excellent and the error ranges were as follows:

Pitch: −0.5 to 0 mm
Total length required: −2 to −3 mm
Gear height: −1.3 to 0 mm
Squareness of teeth: Within ±1 mm
Hardness of tooth surface (H_S): 49 to 52
Roughness of tooth surface: 35 to 50 S.

Thus, all the quality requirements were satisfied.

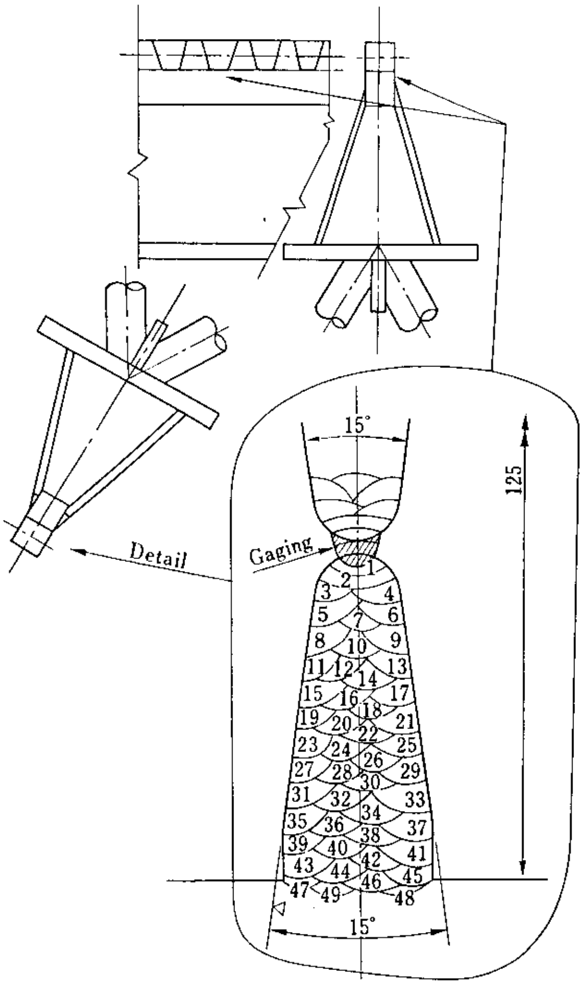
4.2 Welding Procedure Qualification Test

The legs fabricated at this time required double classification of ABS and NK. Prior to actual fabrication, therefore, approval on the welding method was obtained from NK and ABS.

First, joints necessary for fabrication were extracted from the design drawing, and for each of these joints, a welding procedure specification was prepared. An example is shown in **Fig. 18**.

Next, in order to obtain the approval of ABS and NK on the welding procedure specification, a procedure qualification test was conducted using a joint model, witnessed by ABS and NK.

Since the weld portion of pipe joints is difficult to inspect after welding, a production test and a full-sized model test were additionally conducted, as demanded by ABS, but no problem occurred.



Welding conditions

Process	SMAW
Filler metal	KS-116, $\phi 4$
Preheat and interpass temp.	150-200°C
Welding current	130-170 A
Welding volts	22 V
Position	F, OH&V

Fig. 18 An example of welding procedure specifications

4.3 Assembling and Working of Rack and Chord

The chord portion consists of the side plate, guide plate, center rib and diaphragms as shown in **Fig. 17**, and its assembling dimensional accuracy was exceptionally strict for a welded structure. In order to achieve this dimensional accuracy, a special jig for restraint shown in **Fig. 19** was used, and tack welding and seal welding (2 layers) were performed. In order to ensure dimensional accuracy in the height direction and reduce the execution time, machining was applied to the bottom surface of the rack, and the top and bottom surfaces of the center rib and diaphragm, respectively. The guide plate was pre-strained by a press, with welding distortion taken into consideration. The diaphragms were not included in the original design drawing, but for retaining accuracy, they were added at a pitch of about 850 mm, after obtaining the prior approval of ABS and NK. For welding the rack and chord, almost all of which are made of 80 kgf/mm^2 class high strength steel, preheating (100 to 150°C) was necessary. In order to prevent deformation due to non-uniform preheating, hot air was blown into the inner surface of the chord and a panel heater was applied to the external surface of the chord, so that the entire chord would be preheated uniformly.

The rack and chord, which had been supported by a special assembling jig and assembled by manual welding (2 layers), were shifted to a special jig for SAW where guide plate was set at an inclined position of about 45°, and SAW was performed simultaneously from above and below (at the joints between rack and side plate and between side and guide plates). Naturally, hot air preheating was performed at this stage. Forty-eight hours after welding, the weld portions were subjected to the full-line magnetic particle inspection which confirmed that no crack was generated.

4.4 Assembling and Working of Brace

4.4.1 Edge preparation for bracing materials

Bracing includes 3 kinds, i.e., a horizontal brace, diagonal brace and inner brace as shown in **Fig. 17**. Since the edge preparation of the joint was complicated in shape, it was most efficient to use an NC controlled profile cutting machine (Pipe Mat, refer to **Photo 2**), but the joining angle was limited within the range of 30 to 150°. For the inner brace, therefore, full use of the Pipe Mat was possible, but for the horizontal and diagonal braces which included a portion having a joint angle of below 30°, complicated edge preparation had to be employed by the combined use of the Pipe Mat with manual welding and saw cutting.

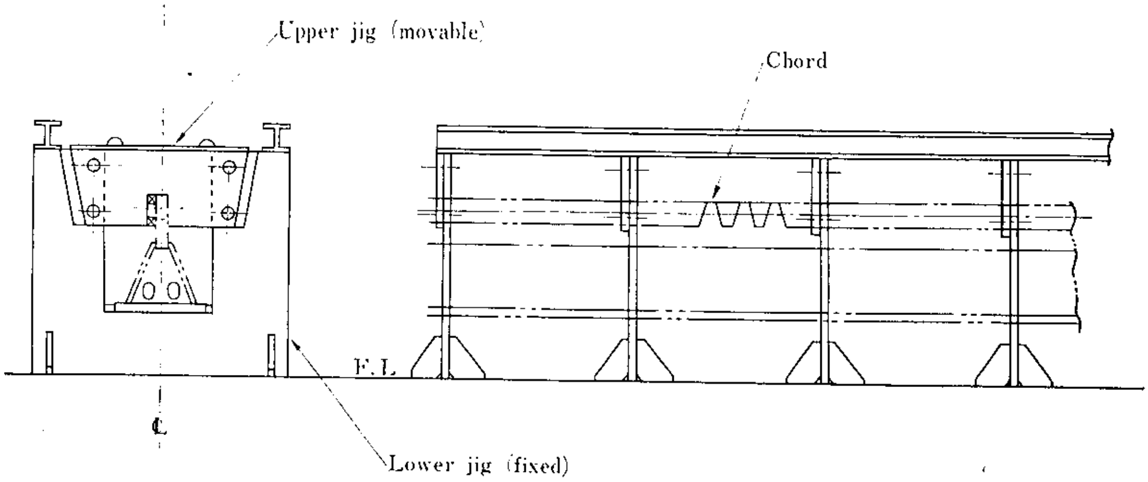


Fig. 19 Jig for chord assembly

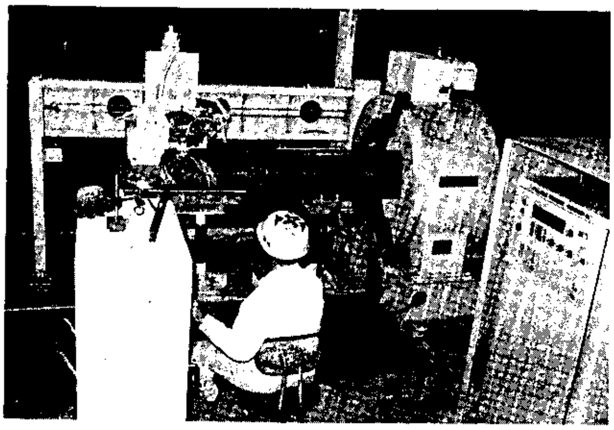


Photo 2 Pipe cutting

4.4.2 Assembling and working of panel unit

A panel unit was assembled by combining three horizontal braces and three inner braces. In assembling this, special jigs were used for welding purposes. This assembled panel unit, which was to be used as a ruler for leg assembling, was worked, so that the distance between the surface in contact with the chord which is composed of the three vertexes of the panel unit and the center of the panel unit would have a dimensional tolerance of within ±0.5 mm.

4.5 Assembling and Working of Leg

As shown in **Fig. 17**, the leg was manufactured by dividing its overall length of about 86 m into 3 blocks of the bottom part (about 19 m), middle part (about 30 m), and top part (about 37 m) according to the customer's request.

Table 17 Dimensions of leg

Position		Block					
		1M	2M	3M	1T	2T	3T
Rack	Ⓟ	−1.0	−1.6	−1.1	−0.7	−1.1	−0.4
	Ⓢ	−1.6	−1.8	−1.0	−1.3	−1.5	−0.3
	Ⓕ	+0.6	+0.7	−1.1	−1.6	−1.1	−1.3
Guide plate	Ⓟ	−0.2	−0.3	−1.6	−0.2	−0.7	−1.8
	Ⓢ	−1.3	−0.9	−0.3	−1.1	−1.2	−0.3
	Ⓕ	−1.4	+1.3	−0.4	−0.4	+0.1	−0.5

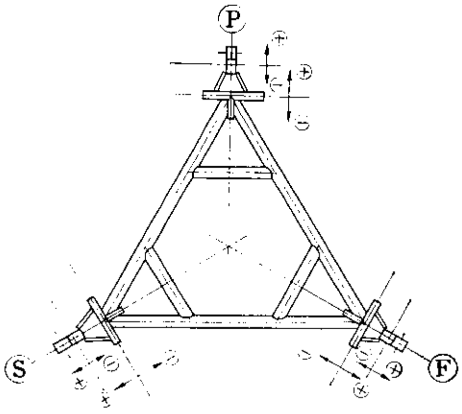


Fig. 20 shows the leg assembling procedure. Two pieces of chords were set on the special assembling jig, and then the panel unit and diagonal brace were sequentially set on the jig. Manual welding was per-

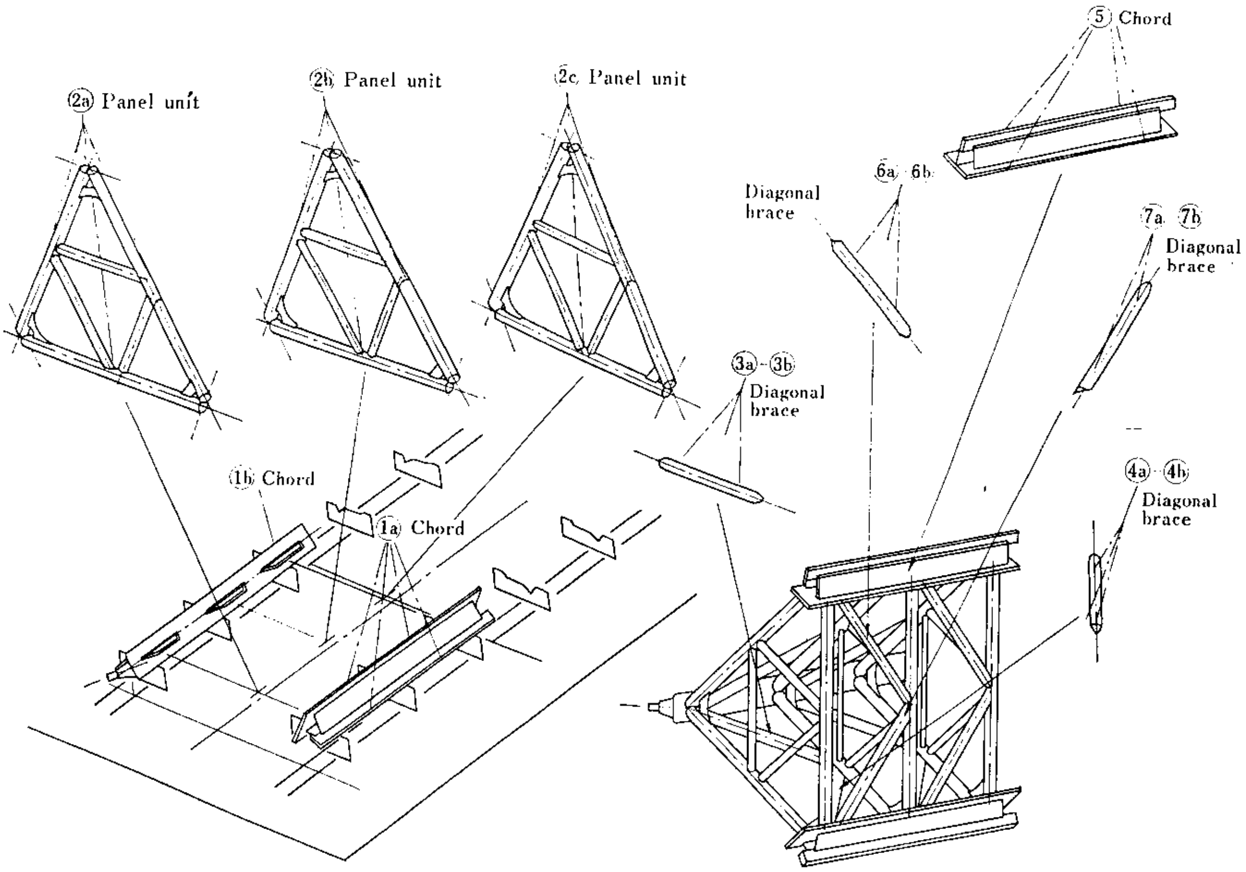


Fig. 20 Assembling process of leg block

formed, in principle, simultaneously at the 3 locations, because if torsion, etc., were allowed to occur, it could not be straightened. Assembling and welding operations were all performed on the surface table at the factory. A plumb was suspended from each chord end, and operation was carried on while dimensional checks were being made at the respective stages.

To facilitate smooth joining of the bottom, middle, and top blocks at the customer's work site, the joining surfaces of the respective blocks were adjusted on the basis of the actual blocks at the factory to check for the correct dimensions.

Table 17 shows the dimensional results of the completed leg, and **Photo 3** its fabricating condition.

4.6 Quality Control

The leg was broadly made of steel plates, pipes (both for structural and piping uses) and shapes, and the strength of these materials spread over a wide range of 40 to 80 kgf/mm^2. In controlling these materials, they were checked by means of control sheets at the time of their acceptance, with their color identified by color painting.

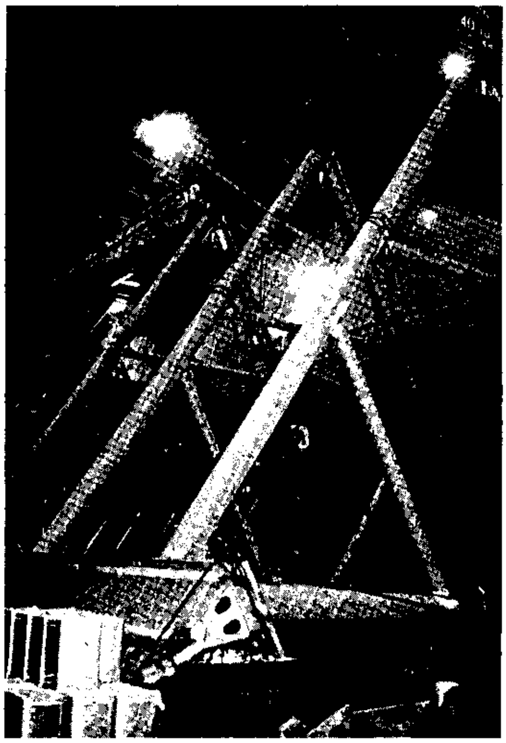


Photo 3 Leg assembling

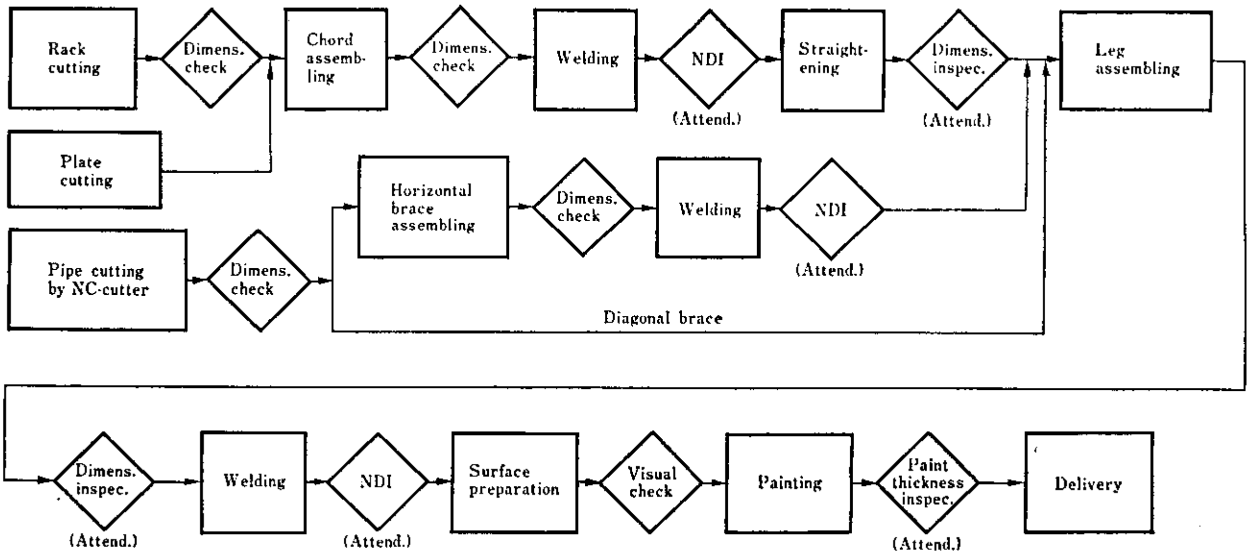


Fig. 21 Flow chart of leg fabrication process

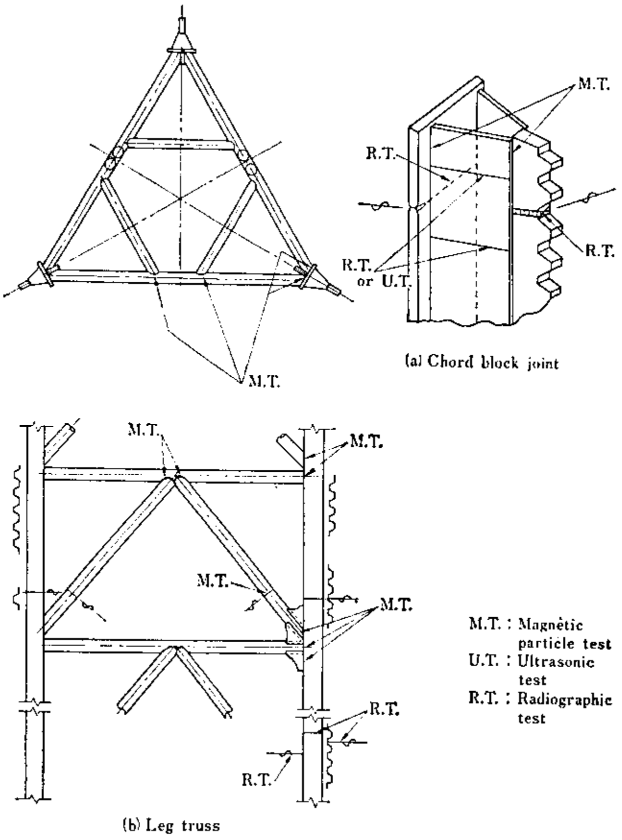
For these materials after gas cutting, collation with the cutting plan was performed, and their dimensions, bevel angles, etc., were recorded into their check sheets to prevent the member materials from being misused later. In order to improve the assembling accuracy of the leg, dimensions of the respective member materials were thoruoghly checked, and those which were out of the proper dimensions were corrected to dimensions within tolerances, on the spot. **Fig. 21** shows check points during leg fabrication.

Since welded portions constituted important locations, quality control, such as issuing of welding materials, and their drying preheating, and interpass temperatures, was thoroughly enforced. Nondestructive tests of the weld were performed according to the customer's specifications by the radiographic test (R.T.), ultrasonic test (U.T.), and magnetic particle test (M.T.) as shown in **Fig. 22.**

In addition, an independent test was performed at Kawasaki Steel by subjecting all the welds to M.T. and the existence of no crack was confirmed.

The applied inspection standards of the welds were as follows:

(1) R.T.: Class 2 or above of JIS Z 3104
(2) U.T.: Class 3 or above of the M detection level of JIS Z 3060
(3) M.T.: ASME Sec. VIII, Div. 1, Appendix VI-1979



(a) Chord block joint

(b) Leg truss

Fig. 22 Applied locations of leg inspection

5 Conclusion

In the above, a description was given on the manufacture, characteristics, and methods of making of steels for fabricating the leg of a jack-up rig on the basis of the actual records of Kawasaki Steel. Since both the steels and welding materials used were produced by the Company, it was possible to obtain the cooperation of various Divisions within the Company, with close inter-divisional mutual understanding. As a result, it was possible to fabricate legs for two jac-kup rigs by completely satisfying strict dimensional accuracy requirements for a welded structure.

Techniques perfected through the above operation will be surely utilized to the full in the future.

Finally, the authors would like to express their deep appreciation to the staff concerned at Hiroshima Dockyard of Mitsubishi Heavy Industries, Ltd. for their valuable technical advice given in the course of fabrication.

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