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Production of Heavy-Gauge Steel Plates Suitable for High-Heat Input Welding in the Arctic Region*



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For application to the energy resources development in the Arctic region, the YP 36 kgf/mm² class structural steel plates (maximum 70 mm in thickness), which have high toughness for high heat input welding, have been developed and manufactured using the multipurpose accelerated cooling system (MACS). This steel contains a small amount of Nb for the purpose of reducing C and Mn contents. Its carbon equivalent is reduced by utilizing MACS and its mechanical properties have satisfied the EH36 steel grade. For the each-side one-pass welding joint with a heat input of 130 kJ/cm, $_{v}E_{-60}$ is more than 10 kgf·m at any notch position. The preheating temperature for crack prevention has been confirmed to be below 0°C by the Y-groove restraint test.

1 Introduction

The recent advance of petroleum resources exploitation projects in the Arctic Ocean requires ever severe properties of steel material for marine structures to be used in this region, especially in higher tensile strength and improved welding efficiency.[1)] The latter calls for lower welding crack susceptibility and higher toughness at high-heat input welding.

The property requirements of steel plates of maximum thickness 70 mm for applications in the Arctic Ocean with guaranteed value YP 36 kgf/mm² are as follows:

(1) YP ≥ 36 kgf/mm², TS ≥ 50 kgf/mm², and toughness $_{v}E_{-60^\circ C} \geq 3.5$ kgf·m with low susceptibility to welding cracks.

(2) At high-heat input welded joints of heat input 130 kJ/cm, the toughness should be $_{v}E_{-60^\circ C} \geq$ 3.5 kgf·m, being suited for the following welding work:
- Each-side, multi-pass welding for plates of thickness 43 mm or greater
- Each-side one-pass welding for plates of thickness between 30 mm and 43 mm
- One-side one-pass welding for plates of thickness 30 mm or smaller

In order to attain such requirements in the Si-Mn based steel plate developed[2)] for high-heat input welding in the Arctic region and maximum thickness increased from 32 mm to 70 mm, examination was made into basic properties of base metal and the properties of high-heat input welded joint using a low Nb-added steel plate having low carbon equivalent ($C_{eq} = \mathrm{C} + \mathrm{Mn}/6 + (\mathrm{Cu} + \mathrm{Ni})/15 + (\mathrm{Cr} + \mathrm{Mo} + \mathrm{V})/5$). In actual manufacture, steel material was processed with the multipurpose accelerated cooling system (MACS), and base metal and welded joint properties were evaluated.

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2 Study on Basic Composition System

For a stable mass production of YP 36 kgf/mm^2 steel plates of thickness up to 70 mm, the addition of Nb and the adoption of the MACS process are effective for ensuring the base plate strength and the strength and low temperature toughness of high-heat input welded joints of 130 kJ/cm input without impairing the weld crack susceptibility. Particularly, to ensure the toughness of welded joints it is necessary to reduce C_{eq}, decrease nitrogen contents, and use the REM (rare earth metal)-Ti treatment.

2.1 Improvement in Toughness of High-Heat Input Welded Joints

Factors for the brittle fracture of high-heat input welded joints are abnormal growth of austenite (γ) grains and the formation of martensite-austenite (M-A) constituent in upper bainitic structure. The following measures are proposed for improving toughness:

(1) Prevention of Abnormal Growth of Grains
To utilize the pinning effect of hardly soluble fine deposites to grain boundaries in the welding heat cycle.

(2) Inhibition of Martensite Formation in Upper Bainite
To reduce C_{eq} by adding Nb and to make fine ferrite-pearlite structure by reducing N content.

2.1.1 Making of fine grains

The toughness of steel plates made under different heat input conditions was compared by using test-pieces produced by the reproducible heat cycles and each-side one-pass welding. Further, the effects of fine deposits and the control method were examined for fusion line (FL) and heat affected zone (HAZ) in the welded joints. **Figure 1** shows the relation of Ti/N ratio to toughness under heat cycles equivalent to different heat inputs by using test pieces having different contents of Ti and N. There is an optimum value around Ti/N ratio = 2.5. **Figure 2** shows the relationship between the maximum temperature in heat cycle, the toughness, and insoluble Ti. At temperatures below 1350°C, a considerable amount of undissolved TiN remains to exert an inhibiting effect to the growth of γ grains. **Figure 3** shows the effect of REM addition to improve the toughness of fusion line area. In the HAZ area which is heated at

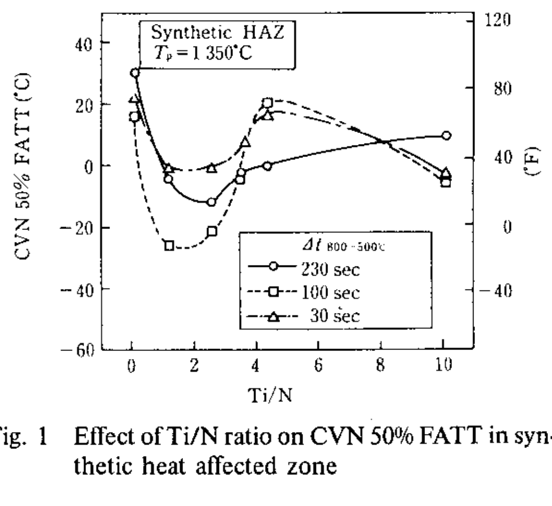

Fig. 1 Effect of Ti/N ratio on CVN 50% FATT in synthetic heat affected zone

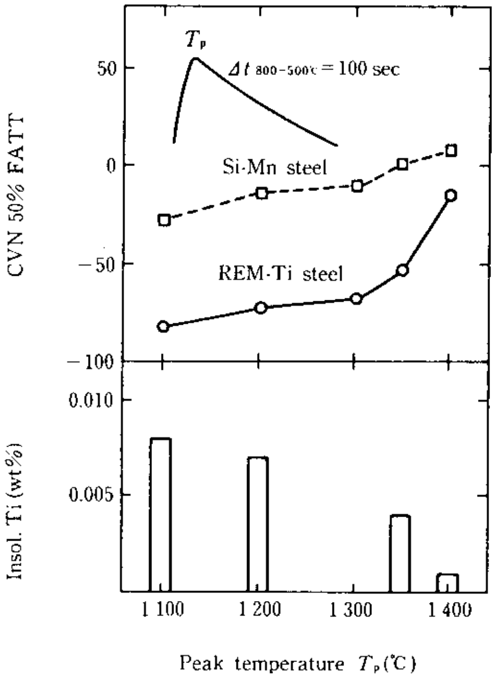

Fig. 2 Relation of peak temperature in synthetic HAZ with toughness and insol. Ti content

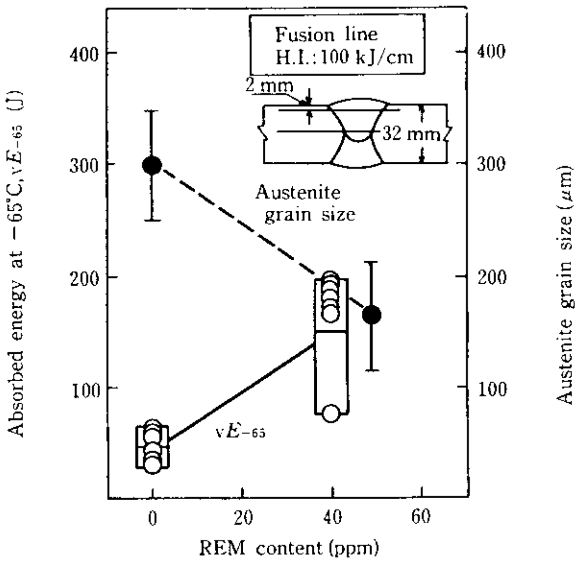

Fig. 3 Effect of REM addition on HAZ toughness

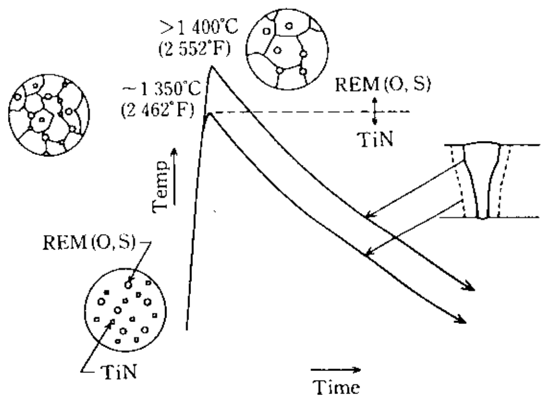

Fig. 4 Schematic model of effect of TiN and REM on austenite grain size at HAZ

1350°C or under, the deposition of fine dispersed TiN inhibites the growth of γ grains, while in the fusion line area where the temperature rises beyond 1350°C, TiN is dissolved and hardly soluble fine REM (O, S) particles inhibit the growth of γ grains. A conceptual diagram of REM-Ti addition effect is shown in **Fig. 4**.

2.1.2 Ferrite-pearlite structure

Figure 5 shows the toughness improving effect of fusion line by reducing C_{eq}. **Figure 6** shows the notable effects of reducing C_{eq}, particularly reducing C and Mn, as well as reducing N.

Summarizing these results, the metallurgical measures to improve HAZ toughness of high-heat input welded joints are shown in **Table 1**.

2.2 Addition of Nb

For a stable mass production of YP 36 kgf/mm^2 steel plates of thickness up to 70 mm, effective means to ensure a high base metal strength without impairing weld crack susceptibility are an addition of a small amount of Nb and the use of the MACS process.[3]

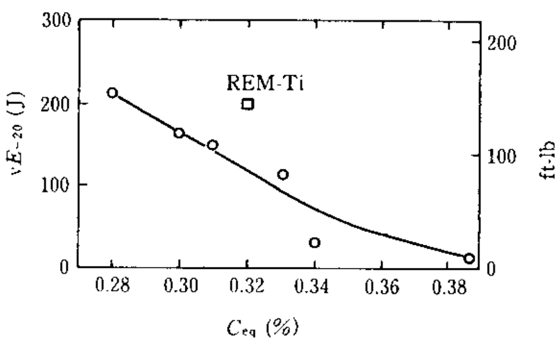

Fig. 5 Relation between carbon equivalent and charpy impact energy of synthetic HAZ at −20°C (Synthetic HAZ: peak temp. 1 350°C, $\Delta t_{800-500°C} = 230$ S-correspoinding to 200 kJ/cm for 25 mm thick plate)

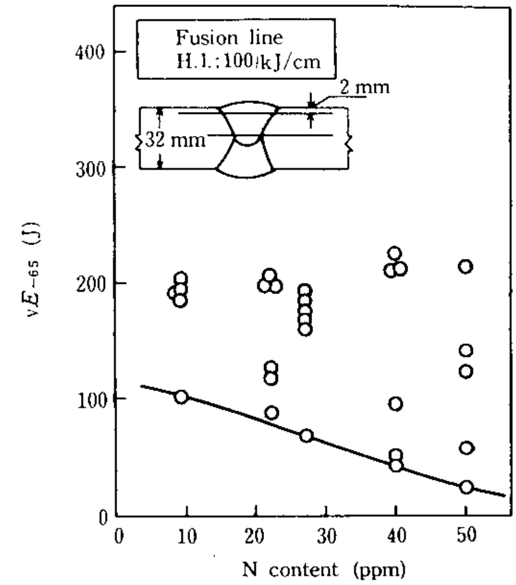

Fig. 6 Effect of N content in steel plate on HAZ toughness

Table 1 Metallurgical action for improving HAZ toughness of high heat input welding

Item	Improvement of HAZ toughness: Metallurgy	Improvement of HAZ toughness: Action
Grain Size	Utilizing pinning effect by insoluble fine precipitate (TiN)	REM-Ti treatment
Microstructure	Decreasing M-A constituent in upper bainitic structure Fine ferrite-pearlite structure	Lowering C_{eq} (MACS process) Lowering C and N and controlling of Ti/N ratio
Matrix	Decreasing free N and sol. Ti	Lowering C and N and controlling of Ti/N ratio

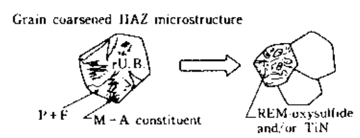

Figure 7 shows the relationship between the toughness of high-heat input welded joints and Nb contents. The optimum Nb content is 0.02% or less. **Figure 8** shows the effect of adding Nb to the base metal strength. From Figs. 7 and 8, it may be concluded that maximum addition of Nb is 0.02% for both strength and joint toughness. **Figure 9** shows the effect of a small amount of Nb addition to improve the strength of the 70 mm thick

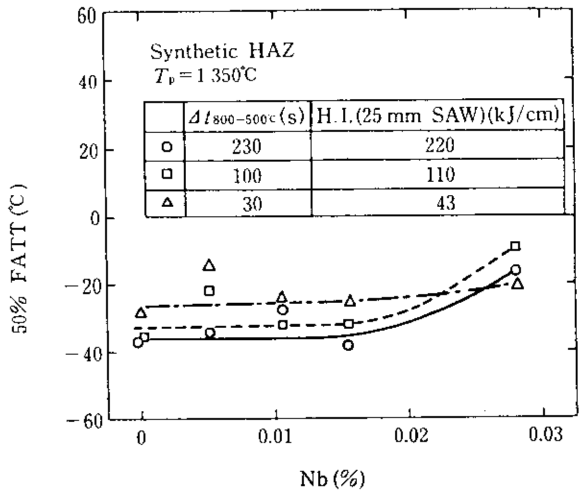

Fig. 7 Relation between Nb content and charpy absorbed energy of synthetic HAZ

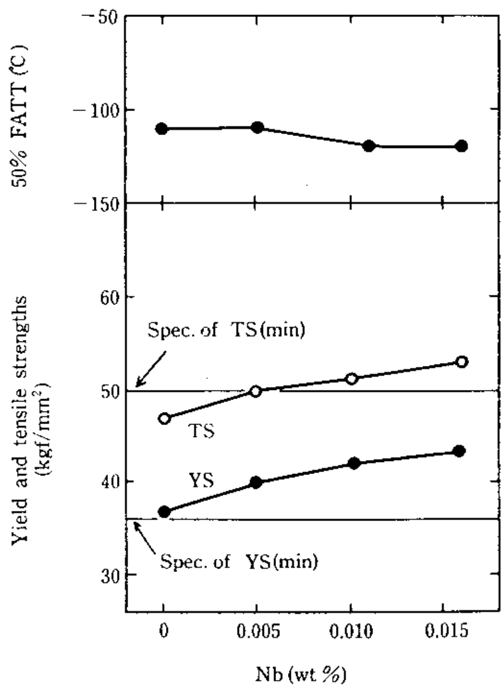

Fig. 8 Effect of Nb addition on yield and tensile strengths of base metal

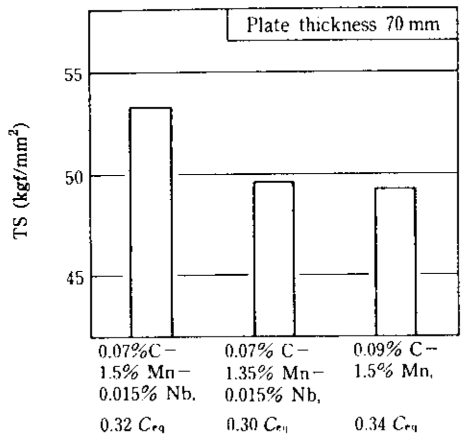

Fig. 9 Effect of Nb addition on tensile strength of accelerated-cooled steel

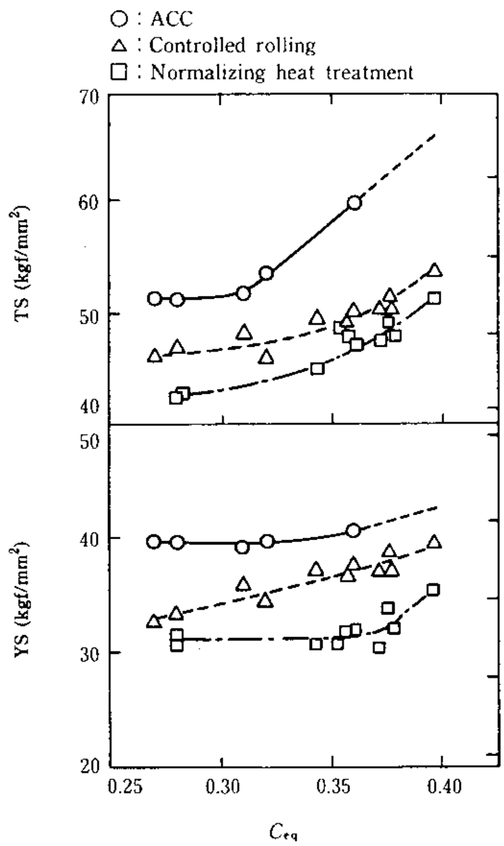

Fig. 10 Relation between carbon equivalent and tensile properties for Si-Mn steel plates

steel plate processed by accelerated cooling. When Nb is not added, tensile strength fails to attain the specified value even if C_{eq} is the highest of 0.34%. In manufacturing plates of thickness up to 70 mm, it is necessary to add 0.015% Nb and assure C_{eq} 0.31% or over. **Figure 10** shows the effect of the MACS process. From Figs. 9 and 10, it can be concluded that the MACS process is very effective for manufacturing low C_{eq} niobium steel.[4)]

3 Properties of Low C_{eq} Niobium Steel Produced by MACS Process

The basic composition of YP 36 kgf/mm² steel plates recommended on the basis of the considerations described in the preceding section is given in **Table 2**. With C_{eq} (IIW) held at 0.36% or less as in case of Si-Mn steel

Table 2 Aimed composition of steel for YP 36 kgf/ mm^2 produced by MACS

(wt %)

C	Si	Mn	P	S	Al	Nb	N	Others*	C_{eq}**	P_{cm}***
0.08	0.30	1.40	≤0.018	≤0.003	0.025	0.015	≤35 ppm	REM-Ti treatment	≤0.36	0.16

* For plate thickness over 40 mm, Cu and/or Ni should be added.

** $C_{eq}=C+\frac{Mn}{6}+\frac{Cu+Ni}{15}+\frac{Cr+Mo+V}{5}$

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

described in the preceding report,[2)] this composition is for the low C_{eq} niobium system with a small addition of Nb and subjected to REM-Ti treatment, in consideration of larger thickness and high-heat input specification. The YP 36 kgf/mm^2 steel plate of this composition was manufactured with the accelerated control cooling (ACC) process, and the properties of base metal and welded joint were evaluated.

3.1 Specimen

The composition of specimens of YP 36 kgf/mm^2 steel manufactured by the MACS process is shown in **Table 3**. Although the thickness is 40 mm, where it is usually difficult to secure toughness by HAZ by the each-side one pass welding in the high-heat input welding, this steel demonstrates the toughness requirement.

Table 3 Chemical composition of steel for YP 36 kgf/ mm^2 of 40 mm thick plate

(wt %)

Grade	C	Si	Mn	P	S	Al	Nb	N	Others	C_{eq}	P_{cm}
EH 36	0.08	0.26	1.34	0.009	0.002	0.024	0.017	23 ppm	REM-Ti treatment	0.30	0.156

3.2 Perperties of Base Metal

3.2.1 Basic properties

Table 4 shows the results of the tensile test and the 2 mm V-notch Charpy impact test of base metal. The strength of base metal well satisfies YP 36 kgf/mm^2 or greater, and TS 50 kgf/mm^2 or greater. The toughness of base metal at −60°C is 3.5 kgf·m, meeting the requirements with ease. Although there is a little reduction of toughness at the middle of the thickness, 50% FATT is as good as −75°C or lower. **Photo 1** shows a photomicrograph of specimen steel, showing fine polygonal mixed grains of ferrite, pearlite, and bainite.

3.2.2 Weld crack susceptibility

Table 5 shows the results of the oblique Y-shaped restraint crack test (JIS Z3158). Temperature for arresting cracks at the surface, section and root is 0°C or lower.

Table 4 Results of tensile test and Charpy impact test

Steel	Location	Direction	Tensile properties			Absorbed energy	CVN 50% FATT
			YP (kgf/mm^2)	TS (kgf/mm^2)	EL (%)	$_vE_{-60}$ (kgf·m)	(°C)
EH 36 t=40 mm	1/4 t	L	44.2 45.0	55.5 56.9	23 23	28.0 31.7 32.0 (30.6)	−85
		C	44.9 44.4	55.4 55.6	24 23	20.8 29.8 25.6 (25.4)	−80
	1/2 t	L	44.5 43.9	55.9 55.7	24 25	28.0 32.5 29.2 (29.9)	−83
		C	45.1 45.0	56.1 56.3	23 23	16.3 18.1 18.6 (17.7)	−75
Aimed	1/4 t	C	≧36	≧50	≧20	≧3.5	—

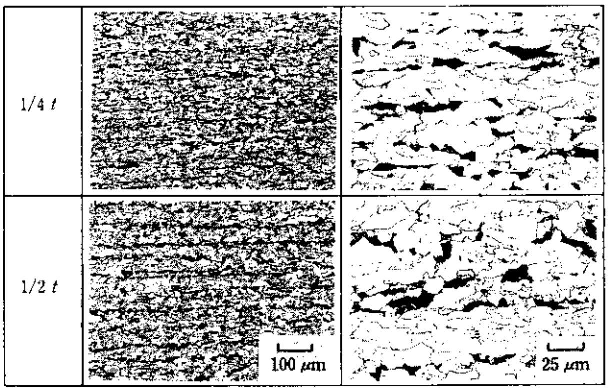

Photo 1 Micrographs of test plate

Table 5 Results of Y-groove restraint cracking test for steel plates

Preheating temp. for crack prevention (°C)		
Surface	Sectional	Root
<0	<0	<0

3.2.3 Fracture toughness of base metal

For an example, **Fig. 11** shows the temperature dependency of crack arrest properties K_{ca} in the direction C obtained by the ESSO test, which is 500 kgf/$mm^{3/2}$ at −40°C.

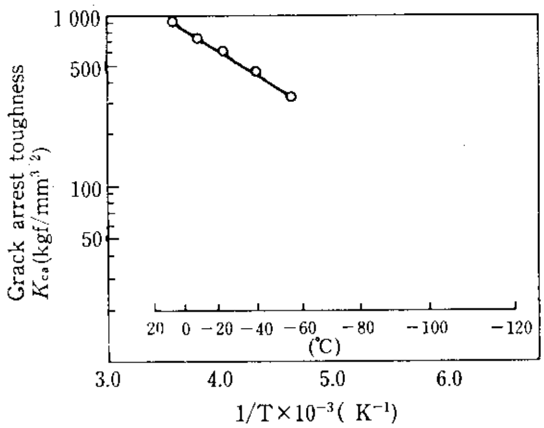

Fig. 11 Results of ESSO test for crack arrest toughness

3.3 Properties of Welded Joints

3.3.1 Welding conditions

Table 6 shows the conditions of an each-side one-pass welding by the KX method[5] with welding heat input 127.5 kJ/cm. The adoption of this process makes it possible to reduce a considerable number of steps in actual production.

3.3.2 Strength of welded joints

The results of a tensile test of NKU 2A test piece are shown in **Table 7**. The fracture occurs at base metal, indicating the strength of base metal.

3.3.3 Charpy impact properties of welded joint

Talbe 8 shows the results of the Charpy impact test of welded joints. The mean absorbed energy at weld metal, bond, and HAZ within 2 mm from the bond at −60°C was 10 kgf·m or more, indicating the satifactory impact properties.

Table 6 Welding conditions of each side one pass welding

Welding material	Pass No.		Current (A)	Arc voltage (V)	Travel speed (mm/min)	Heat input (kJ/cm)
KB 110 KW 50 C (M)	Backing side	L	1 300	32	55	99.4
		T	1 100	45		
	Finishing side	L	1 300	32	45	127.5
		T	1 200	45		

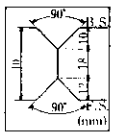

Table 7 Tensile strength of each side one pass welded joint

Specimen	TS (kgf/mm²)	Fracture location
No. 1	56.1	Base metal
No. 2	56.5	Base metal

Table 8 Results of Charpy impact test at high heat input welding joint of steel plates

Notch location		Absorbed energy (kgf·m)			50% FATT (°C)
		$_vE_{-40}$	$_vE_{-60}$	$_vE_{-80}$	
Finishing side	WM	19.1	17.1	8.6	−75
	Bond	18.3	11.8	6.7	−63
	HAZ 2	17.6	14.4	8.5	−66
Backing side	WM	22.4	20.2	12.7	−82
	Bond	22.3	17.2	6.7	−71
	HAZ 2	21.9	20.3	14.8	−86

4 Commercial Production

Specimens described in Sec. 3, of both base metal and weld metal, proved to well satisfy the required properties. The commercial production was carried out on the basis of these results.

(1) Required Properties
Table 9 shows mechanical properties required of steel to be used in the Arctic Ocean.

(2) Properties of Base Metal
Figure 12 shows the strength and toughness of steel plates in the commercial production. Both strength and toughness of base metal fully satisfy the requirements.

(3) Properties of Weld Zone
The toughness of welded joints obtained, respectively, by the each-side one-pass welding of 40 mm thick plates and by the each-side multi-pass welding of 70 mm thick plates, are shown in **Table 10**. It has

Table 9 Requirements for mechanical properties of steel

Steel grade	EH 36 produced by MACS process
Tensile properties	YP ≥36 kgf/mm² TS ≥50 kgf/mm²
Impact properties	−50°C
Impact properties of high-heat-input-welded joints (SAW I, SAW II, SAW III, and CO_2 welding*)	$_vE_{-50}$ ≧3.5 kgf·m

* Maximum heat input level for plates: SAW I (each side one pass welding of less than 43 mm*t* plates), 130 J/cm; SAW II (each side multi pass welding of from 43 mm to 70 mm*t* plates), 100 J/cm; SAW III (one side one pass welding of less than 25 mm*t* plates), 130 J/cm; CO_2 welding of less than 20 mm*t* plates, 50 J/cm.

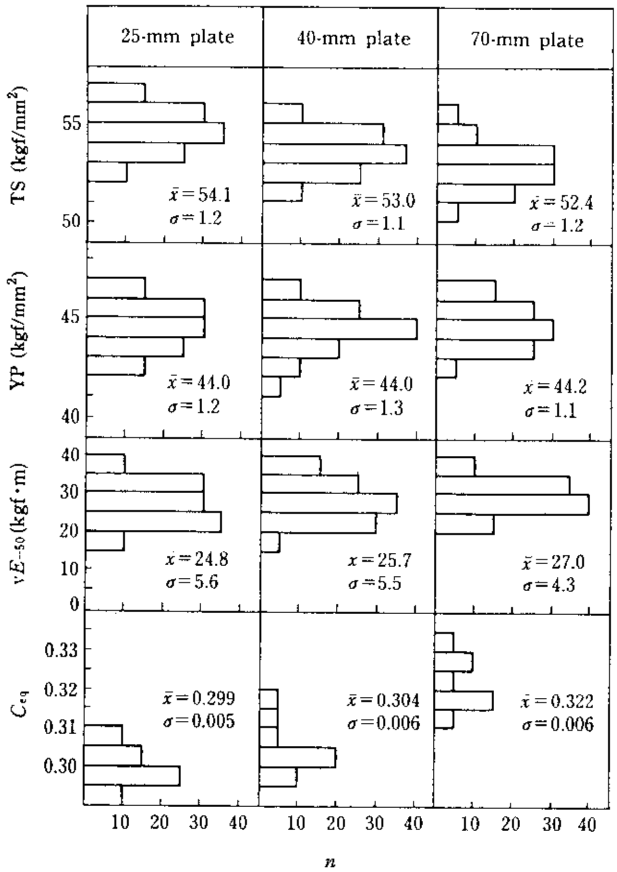

Fig. 12 Results of tensile properties and impact properties of steel plates at commercial production level

Table 10 Results of Charpy impact test at high heat input welding joint of steel plates at commercial production level

Plate thickness (mm)	Heat input (kJ/cm)	Notch location	Absorbed energy (kgf·m) $_vE_{-50}$
40	127.5 (Each side one pass welding)	WM	17.7
		Bond	15.3
		HAZ 1 mm	17.1
		HAZ 3 mm	13.7
		HAZ 5 mm	27.2
70	104 (Each side multi pass welding)	WM	15.9
		Bond	14.3
		HAZ 1 mm	17.8
		HAZ 3 mm	14.0
		HAZ 5 mm	28.2

been proved that the required toughness can be fully guaranteed of welded joints at −60°C even with commercial products.

(4) Production Records

Table 11 shows the production records of YP 36 kgf/mm² steel for cryogenic districts. The stable mass production of the low C_{eq} niobium containing high-heat input steel plates for the Arctic Ocean use has been established.

Table 11 Production records of steel plates for offshore structure

	Case 1	Case 2
Type of structure	Caisson	Semi-submersible rig
Operation field	North sea	North sea
Maximum thickness	70 mm	50 mm
Production period	Sep. 1986-Dec. 1985	Aug.-Nov. 1985
Quantity of plates		
MACS plates	25 000 t	12 000 t
Others (as-rolled)		1 000 t

Consequently, it has been confirmed that steel plates produced by the MACS process have little fluctuation in mechanical properties of both base metal and welded joint, and can sufficiently be put to stable mass production.

5 Conclusion

A low C_{eq} niobium containing YP 36 kgf/mm² steel manufactured with MACS process for the Arctic Ocean use was examined in mechanical properties of base metal and welded joints. The steel plates have stable strength and toughness at the high-heat input welded joints of 130 kJ/cm heat input, with strength and toughness guaranteed of base metal at thickness up to 70 mm.

These steel plates are currently at the level of stable mass production, and can satisfy the specifications at −80°C. The range of application for offshore structures in the Arctic Ocean is expected to expand further.

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