KAWASAKI STEEL TECHNICAL REPORT
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Structural Steel Plates for Arctic Use Produced by Multipurpose Accelerated Cooling System

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Synopsis :
Arctic use of the YP 36kgf/mm2 class structural steel plate for high heat input welding was developed by using Multipurpose Accelerated Cooling System (called "MACS") which was established in April 1983 at Mizushima Works, Kawasaki Steel Corp. The characteristics of the steel (32 min in thickness) are summarized as follows: (1) Fracture appearance transition temperature at middle thickness in the transverse direction was lower than -100℃, the COD value (δc) at -60℃ was higher than 1.0 mm, and the corresponding temperature to a crack arrest toughness (Kca) of 600 kgf/mm3/2 was -60℃. It can be concluded from the above that the material has sufficient resistively to brittle crack initiation and crack initiation and crack propagation. (2) At both one-side two-pass and two-side one-pass welding joints with high heat input, VE-60 was more than 7 kgf m at any notch position and δc at -60℃ notched on the fusion line was 0.3 mm or more. (3) The preheating temperature for crack prevention was confirmed to be below 0℃ by the y-groove, large scale fillet restraint weld cracking test.

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Structural Steel Plates for Arctic Use Produced by Multipurpose Accelerated Cooling System*



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Arctic use of the YP 36 kgf/mm^2 class structural steel plate for high heat input welding was developed by using Multipurpose Accelerated Cooling System (called "MACS") which was established in April 1983 at Mizushima Works, Kawasaki Steel Corp. The characteristics of the steel (32 min in thickness) are summarized as follows:

(1) Fracture appearance transition temperature at middle thickness in the transverse direction was lower than−100°C, the COD value (δ_c) at −60°C was higher than 1.0 mm, and the corresponding temperature to a crack arrest toughness (K_{ca}) of 600 kgf/mm$^{3/2}$ was −60°C. It can be concluded from the above that the material has sufficient resistivity to brittle crack initiation and crack propagation.

(2) At both one-side two-pass and two-side one-pass welding joints with high heat input, ${}_{\mathrm{v}}E_{-60}$ was more than 7 kgf·m at any notch position and δ_C at −60°C notched on the fusion line was 0.3 mm or more.

(3) The preheating temperature for crack prevention was confirmed to be below 0°C by the y-groove, large scale fillet restraint weld cracking test.

1 Introduction

In the Arctic region around the Beaufort Sea off-Northern Alaska, petroleum is being actively exploited. The hull and off-shore structures used in the Arctic region require steel plates of high tensile strength so as to reduce total weight. Not only that, for attaining higher welding efficiency, the steel plate must have low susceptibility to weld zone cracking at cryogenic temperatures and superior toughness at weld joints of high heat input. While steel plates of YP ranging from 36 kgf/mm^2 to 70 kgf/mm^2 are used prevalently for this purpose, the YP 36 kgf/mm^2 class is currently favored. Requirements for the 36 kgf/mm^2 class steel plates for use in the Arctic region include

(1) Superior toughness of base metal and of welded joints subjected to a high heat input such as in the two-sides one-pass welding or one-side two-pass welding.
(2) Low susceptibility to welding crack at cryogenic temperatures.

The process for rendering these properties to steel plates is a water-cooled controlled rolling method that combines controlled rolling and post-rolling controlled cooling(ACC). The former by use of the non-water-cooled controlled rolling method called KTR(Kawasaki Thermomechanical Rolling)[1], the latter by the Multipurpose Accelerated Colling System(MACS)[2]. The present report deals with the mechanical properties of the base metal and the welded joint of the steel plate manufactured by the MACS-ACC (hereinafter simply called MACS), in comparison with those of steel plates of the same thickness manufactured through the KTR.

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Table 1 Chemical compositions of steels for YP 36 kgf/mm² arctic use produced by MACS and KTR (wt%)

Steel	C	Si	Mn	P	S	Al	Cu	Ni	V	Ti	REM	C_{eq}
MACS (ACC)	0.06	0.27	1.47	0.008	0.001	0.038	—	0.40	—	0.010	0.006	0.33
KTR	0.07	0.37	1.52	0.008	0.001	0.041	0.16	0.55	0.04	0.011	0.006	0.38

2 Steel Plate Specimens

EH36 steel plates 32 mm thick manufactured by the MACS process, and those manufactured by the KTR process were used for the present study, with the latter as comparison. The chemical compositions of the test pieces are shown in **Table 1**. The KTR steel plate for comparision contains 0.38% carbon equivalent, with REM and Ti added and designed for high heat input welding. The MACS steel plates have coefficients representing the weld hardening characteristics, C_{eq}, and the weld crack susceptibility P_{cm}, 0.33% and 0.15%, respectively, fairly lower than those of conventional non-water-cooled, hull structural 50 kgf/mm² steel plates. This is due to the reduced C- and Ni-contents and the omission of Cu and V additions as is clear from the comparison with the chemical composition of KTR steel used for comparison. In the MACS steel, the reduction of C_{eq} and P_{cm} values is achieved by the improvement of strength through the introduction of the second phase microstructure in the controlled cooling process. On the other hand, the low temperature toughness required for steel plate is improved by homogenizing fine γ grains at lower slab reheating temperature, by using the controlled rolling before controlled cooling, and by suppressing grain growth in the controlled cooling process[3,4].

In order to assure high toughness at the high heat input welded joint with a weld heat input of 100 kJ/cm or more, ① C_{eq}, or C-content, in particular, is reduced, ② REM-Ti treatment is conducted, ③ N-content is reduced, and ④ an optimum amount of Ni is added to stabilize the toughness. The Ni also contributes to raising the strength and toughness of the base metal.

In addition to the foregoing designing of basic chemical composition, efforts are made to lower the P- and S-contents aiming to reduce the non-metallic inclusions which are the origins of brittle fracture, and further to improve the anisotropy of the mechanical properties.

3 Mechanical Properties of Base Metal

3.1 Tensile Properties

Table 2 shows the results of the tensile test in L-, T- and Z-directions. The MACS plates have YP 38–40 kgf/mm² and TS 51–54 kgf/mm², despite their lower C_{eq}, and also the reduction in area in the Z-direction is 77% or over. This proves that the plate can perform adequately as lamellar-tear-resistance steel.

Table 2 Tensile test properties of steel plates

Process	Direction	YP (kgf/mm²)	TS (kgf/mm²)	El (%)	RA (%)
MACS (ACC)	L	38 39	53 54	27 26	— —
	T	39 39	53 53	26 25	— —
	Z	39 41 40	51 51 51	19 20 20	77 78 78
KTR	L	42 42	52 52	29 29	— —
	T	46 45	54 54	27 27	— —
	Z	43 43 43	53 53 53	20 19 19	82 81 79

L- and T-Direction: NKU No. 1 specimen
Z-Direction: Diameter=10 mm, G.L.=50 mm

3.2 Charpy Impact Properties

Table 3 shows the results of the Charpy impact test using 32 mm thick plate at 1/4 of thickness. The absorption energy of MACS plate at −60°C in directions paral-

Table 3 Results of charpy impact test

Process	Direction	Absorbed energy (kgf·m) $_vE_{-40}$	$_vE_{-60}$	$_vE_{-80}$	$_vE_{-100}$	$_vE_{-120}$	CVN50% FATT (°C)
MACS (ACC)	L	30.4 31.7 32.3 (31.5)	28.0 31.7 32.0 (30.6)	27.1 29.6 31.3 (29.3)	19.9 21.6 23.8 (21.8)	17.7 14.9 13.8 (15.5)	−120
	T	30.0 32.0 27.3 (29.8)	28.3 27.3 26.3 (27.3)	22.2 24.2 21.5 (22.6)	20.0 16.7 14.8 (17.2)	3.1 2.6 3.0 (2.9)	−111
KTR	L	30.0 31.2 31.2 (30.8)	30.4 30.4 31.3 (30.7)	25.6 30.6 25.6 (27.1)	17.1 17.5 17.0 (17.2)	16.8 16.4 17.2 (16.8)	−140
	T	30.9 33.3 26.8 (30.3)	26.0 26.9 17.9 (23.6)	16.3 19.5 24.2 (20.0)	12.9 14.6 11.2 (12.9)	8.0 7.3 8.6 (8.0)	−132

( ) Average

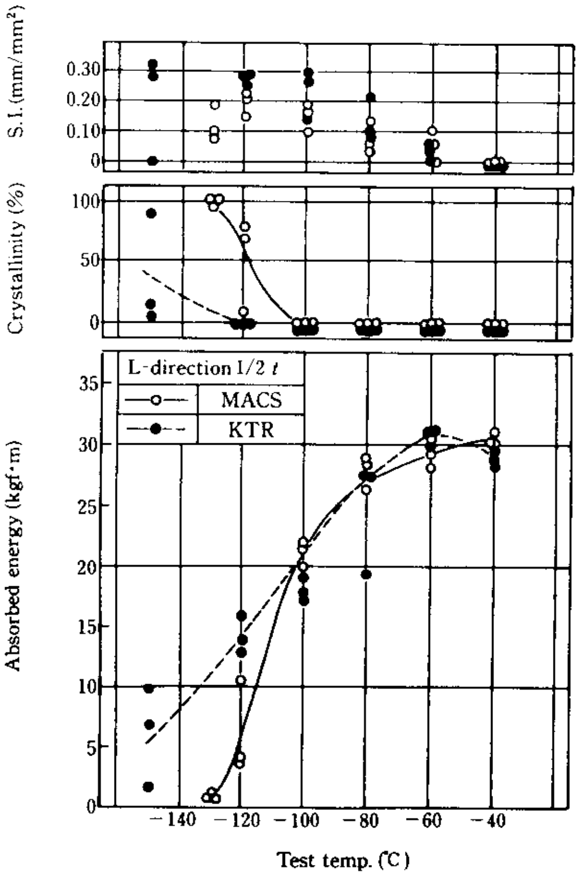


Fig. 1 Transition curves of Charpy impact test on the specimens taken in the thickness direction from the middle of a 32-mm thick plate

lel and transverse to rolling is as high as 26 to 32 kgf · m, and the fracture appearance transition temperature ${}_{v}T_{rs}$ is −110°C or under. Examples of Charpy impact properties measured at the middle of thickness are shown in **Fig. 1**. Both absorption energy and ${}_{v}T_{rs}$ are comparable to those at 1/4 thickness. Figure 1 jointly shows the results of the comparison material (KTR plate), of which ${}_{v}T_{rs}$ is lower than that of MACS plate. This may be attributed to the more frequent occurrence of separations in KTR plate.

4 Fracture Toughness of Base Metal

4.1 Brittle Fracture Initiation

Results of the three-point bending test (COD test) using 32 mm thick plate and those of through thickness tests are shown in **Table 4** and **Fig. 2**, respectively. The critical COD values of both MACS and KTR plates at −60°C are 1.4 mm or over in the L- and T-directions. The δ_C value in the through thickness direction (Z-direction) is 0.25 mm or over at −60°C.

Table 4 Results of three point bending test

Process	Direction	Temp. (°C)	Critical COD (mm)	
MACS (ACC)	L	−40	2.039,	1.752
		−60	1.630,	1.666
		−80	1.690,	1.667
	T	−40	1.509,	1.618
		−60	1.391,	1.413
		−80	1.378,	1.157
KTR	L	−40	2.215,	2.437
		−60	2.058,	2.346
		−80	2.115,	2.225
	T	−40	2.122,	1.355
		−60	2.072,	1.658
		−80	1.467,	1.419

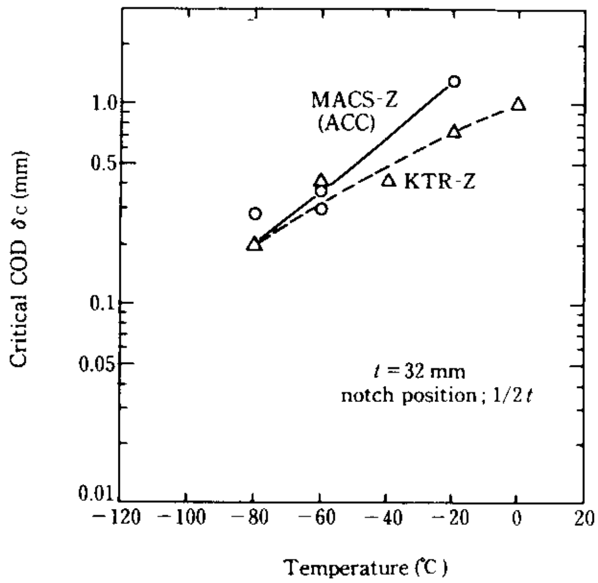


Fig. 2 Results of three point bending test in through thickness direction

4.2 Brittle Crack Arrest Toughness (ESSO Test)

Figure 3 shows the temperature dependence of brittle crack arrest toughness K_{ca} in the T-direction, as obtained by the ESSO test. While points for KTR plates which have greater separation index and lower ${}_{v}T_{rs}$ display lower temperatures than those of MACS plate, K_{ca} value of the MACS plate at −60°C is 620 kgf/mm$^{3/2}$, exhibiting adequate performance as a brittle fracture arresting plate[5].

5 Welding Crack Susceptibility at Low Temperature

The results of *y*-groove restraint weld cracking test, of JIS Z 3158 are shown in **Table 5**. The crack prevention

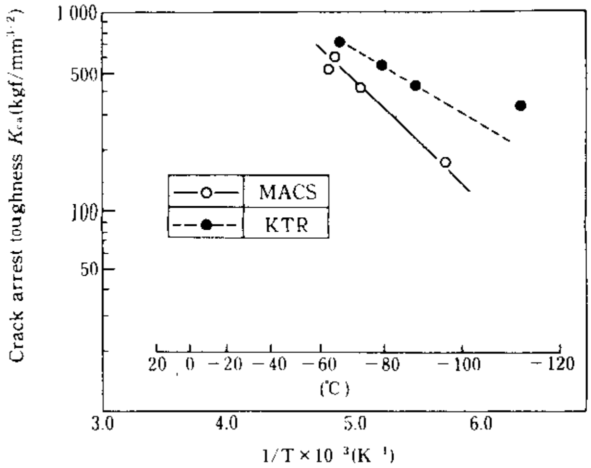
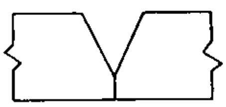
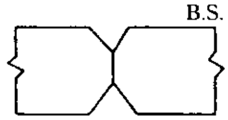


Fig. 3 Results of ESSO test for crack arrest toughness

Table 5 Results of y-groove cracking test for steel plates produced by MACS process

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

Table 6 Welding method for high heat input welding

Welding	Heat input (kJ/cm)		Groove Design
One side two pass SAW	1 pass	120 ~ 95	
	2 pass		
Each side one pass SAW	B.S.	85 ~ 110	
	F.S.		

pre-heating temperature for surface, section and root crack is lower than 0°C. In the low heat input over-head and horizontal fillet weldings, at 0°C specimen temperature, no cracks attributable to the inherent property of the steel plate itself can be seen, demonstrating its excellent resistance to weld crackings.

6 Basic Properties of Welded Area

6.1 Welding Conditions

Welding conditions for the one-side, two-pass SAW and the two-side one-pass SAW are shown in **Table 6**. In both welding processes, the heat input is as high as 100 kJ/cm.

Table 7 Tensile test results at high heat input welding joint of steel plates produced by MACS process

Welding	*TS* (kgf/mm²)	Fracture location
One side two pass	54.9	BM
	55.4	BM
Each side one pass	55.8	BM
	55.7	BM

BM: Base metal

6.2 Strength of Welded Joint

The results of tensile test for joint with NKU 2A test piece are shown in **Table 7**. The fracture occurs at the base metal in all of the welding methods. The tensile strength for C_{eq} 0.33% and high heat input welding of 100 kJ/cm is 54 kgf/mm², which is comparable to that of the base metal.

6.3 Charpy Impact Properties of Welded Joint

The results of a Charpy impact test using specimens taken at 2 mm (around 1/4 *t*) and 1/2 *t* from the surface of the final welding pass are shown in **Table 8**. The average absorption energy at −60°C is 7 kgf·m or over in

Table 8 Results of charpy impact test at high heat input welding joint of steel plates produced by MACS process

Welding method	Notch location		Absorbed energy at −60°C (kgf·m)	$_vT_{rs}$ (°C)
One side two pass SAW	Sub-surface	WM	11.4	−71
		Bond	14.7	−81
		HAZ 2	10.8	−82
	$\frac{1}{2}t$	WM	7.0	−56
		Bond	19.5	−60
		HAZ 2	17.5	−66
Each side one pass SAW	Sub-surface	WM	18.7	−85
		Bond	9.1	−60
		HAZ 2	24.4	−71
	$\frac{1}{2}t$	WM	20.6	−87
		Bond	17.4	−86
		HAZ 2	22.0	−89

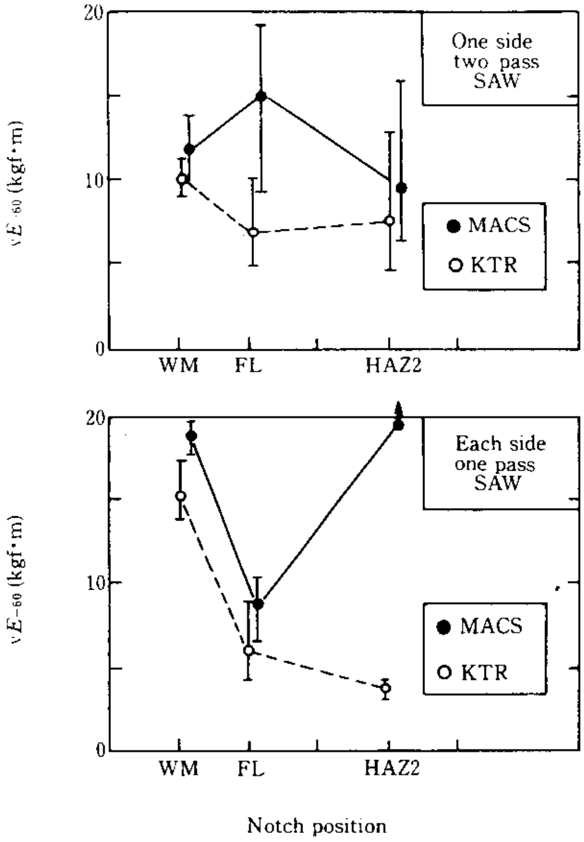


Fig. 4 Results of charpy impact test at high heat input welding joint

any welding process, thickness level and notch position. As shown in **Fig. 4**, the individual values of absorption energy at −60°C for MACS plate are greater than 5 kgf · m, proving an adequate Charpy impact property.

7 Fracture Toughness of Welded Joint

7.1 Brittle Fracture Initiation in Small Scale Test

With regard to the initiation of brittle fracture at the welded joint produced by one-side two-pass SAW and two-side one-pass SAW, shown in Table 6, a 32 mm full thickness COD test was conducted. The results are shown in **Figs. 5** and **6**. The critical COD values of the FL and HAZ portions of the MACS plate were 0.35 mm or over at −60°C in both welding processes.

7.2 Brittle Fracture Initiation in Large Scale Test

The large scale cross joint tensile test was conducted on welded joints produced by one-side two-pass SAW and two-side one-pass SAW with residual stress applied by the multi-layer SAW and a 64 mm through-thickness notch (0.2 mm notch tip) made at the weld bond. The results are given in **Table 9**. The fracture stress at −60°C under severe conditions involving angular distortion is 36 kgf/mm^2 or over in terms of gross stress, which is comparable to that of the base metal.

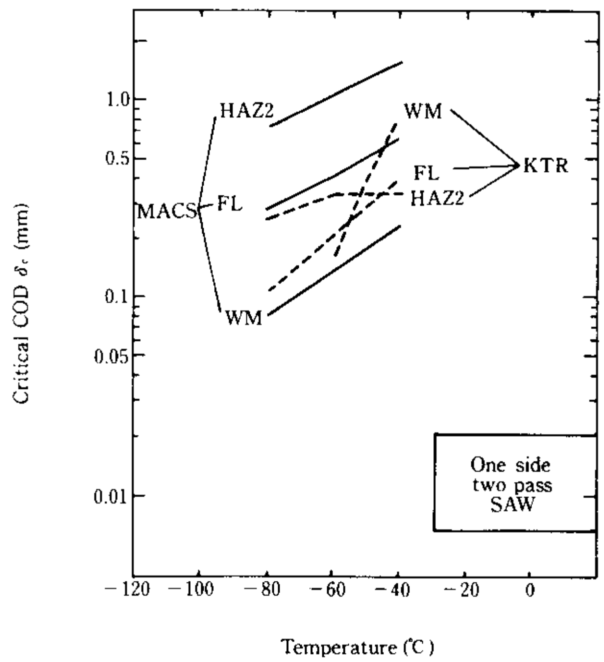


Fig. 5 Results of three point bending test at one-side two-pass SAW high heat input welding joint

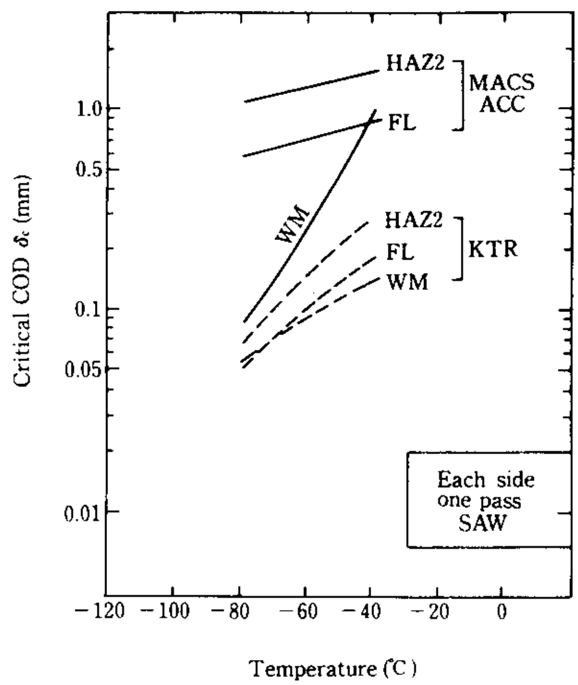


Fig. 6 Results of three point bending test at each-side one-pass SAW high heat input welding joint

Table 9 Results of wide-width center-notched tensile test under residual stress for brittle fracture initiation

Process	Welding method	Angular distortion (mm)	Fracture stress (kgf/mm²) Gross stress	Fracture stress (kgf/mm²) Net stress	Fracture toughness K_C (kgf/mm$^{3/2}$)
MACS (ACC)	Each side one pass SAW	3.9 2.3	39.6 40.8	44.4 45.8	402 414
	One side two pass SAW	2.1 4.5	41.8 43.8	46.8 49.1	424 445
KTR	Each side one pass SAW	9.2 10.2	41.5 40.3	46.6 45.2	421 410
	One side two pass SAW	5.9 5.3	40.1 45.9	45.4 51.5	422 466

8 Conclusion

For the application to arctic off-shore structures, the mechanical properties of base metal and high heat input welded joints for low carbon 32 mm thick steel plates of YP36 kgf/mm^2 grade, manufactured by the MACS process were tested. As a result, it was proved that the said steel plates can be welded without reheating, and that the base metal and high heat input welded joint of 100 kJ/cm weld heat input of these plates are more than adequate, possessing a margin of safety with respect to the brittle fracture initiation and to the crack propagation arrest at temperatures as low as −60°C. On the basis of these results, it is felt that the application of the MACS process can be extended to the production of steel plates of low temperature tank vessels and extra thick steel plates for use in the Arctic.

References

1) C. Shiga, T. Hatomura, J. Kudo, A. Kamata, K. Hirose, and T. Sekine: "Development of Large-Diameter High Tensile Strength Linepipe for Low Temperature Services." *Kawasaki Steel Giho*, **13**(1981)1, 106
2) S. Ebata, S. Bando, N. Hirai, R. Tarui, N. Ikeya, and M. Yoshihara: *Kawasaki Steel Giho*, **16**(1984)2, 241
3) C. Shiga, T. Hatomura, K. Amano, T. Enami: *Tetsu-to-Hagané*, **68**(1982)10, A227
4) Y. Saito, M. Kimura, M. Tanaka, T. Sekine, K. Tsubota, and T. Tanaka: "Controlling of Microstructure and Mechanical Properties by Utilizing Deformation Resistance in Plate Rolling," *Kawasaki Steel Giho*, **15**(1983)4, 241
5) R. Nagamoto, M. Ushijima, A. Kawamura, H. Yajima, and M. Tada: *Journal of Society of Naval Architects of Japan*, **152**(1983), 405