KAWASAKI STEEL TECHNICAL REPORT

No.13 (September 1985)

Properties of YP 36-kgf/mm2 Class Hull Structural Steel Plates Produced by Accelerated Control Cooling Process

Yoshihumi Sannomiya, Hiroshi Nishizaki, Jun Nagai, Chiaki Shiga, Hisae Terashima, Toshihiro Sekine

Synopsis :

Online thermomechanical controlled cooling system named MACS (Multipurpose Accelerated Cooling System) was set into operation in April 1983 at No. 2 Plate Mill at Mizushima Works, Kawasaki Steel Corporation. The mechanical properties of YP 36 kgf/mm2 (350 MPa) class hull structural steel plates of A, D, and E grades manufactured by the MACS process, have been investigated. The plates, manufactured by the MACS process, having 0.05 to 0.09% lower carbon equivalent than usual, are superior to conventional steel plates in the welding crack and toughness at the heat affected zone of a large heat input welded joint. The values of tensile and fatigue tests both in base metal and in the large heat input welded joint, are satisfactory. The application of the MACS device to producing higher strength steel with lower Ceq will introduce the increase in the amount of higher strength hull structural steel plates based on the superior characteristics of their mechanical properties.

The body can be viewed from the next page.

KAWASAKI STEEL TECHNICAL REPORT No. 13 September 1985

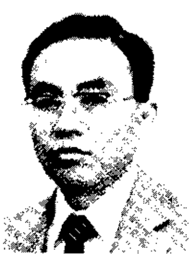
Properties of YP 36-kgf/mm² Class Hull Structural Steel Plates Produced by Accelarated Control Cooling Process*



Yoshifumi Sannomiya
Staff Manager,
Plate Control Sec.,
Mizushima Works

Hiroshi Nishizaki
Plate Control Sec.,
Mizushima Works

Jun Nagai
General Manager,
Technical Control
Dept., Mizushima
Works



Chiaki Shiga
Dr. Engi., Chief of
Plate Research Lab.,
I & S Research Labs.

Hisae Terashima
Dr. Engi., Senior
Researcher, Plate
Research Lab.,
I & S Research Labs.

Toshihiro Sekine
Staff General Manager,
Technical Control
Dept., Chiba Works

Synopsis:

Online thermomechanical controlled cooling system named MACS (Multipurpose Accelerated Cooling System) was set into operation in April 1983 at No. 2 Plate Mill at Mizushima Works, Kawasaki Steel Corporation. The mechanical properties of YP 36 kgf/mm² (350 MPa) class hull structural steel plates of A, D, and E grades manufactured by the MACS process, have been investigated. The plates, manufactured by the MACS process, having 0.05 to 0.09% lower carbon equivalent than usual, are superior to conventional steel plates in the welding crack and toughness at the heat affected zone of a large heat input welded joint. The values of tensile and fatigue tests both in base metal and in the large heat input welded joint, are satisfactory.

The application of the MACS device to producing higher strength steel with lower C_{eq} will introduce the increase in the amount of higher strength hull structural steel plates based on the superior characteristics of their mechanical properties.

1 Introduction

Against the background of the growing energy saving trend in recent years, needs for reducing the weight of the hull structure became stronger, and active efforts have been made in increasing the strength of hull structure steel plates.[1] High tensile steels can be made by increasing carbon equivalent (C_{eq}) only at the expense of weldability, therfore, a development of high tensile steels with improved weldability became indispensable.

One of such improvements was the controlled rolling technique. This technique permitted a decrease in C_{eq} of TS 50-kgf/mm² class high tension steel, for instance, from 0.43 to about 0.38,[2] but this was the limit of the C_{eq} decrease achievable by the controlled rolling, and the increase in strength of steel plates was confined mainly to a YP 32-kgf/mm² class steel which had a comparatively satisfactory weldability.

With such a background, the controlled cooling technique is a process to produce steel plates of the same strength at a lower C_{eq} value than in those manufactrured by the conventional controlled rolling technique, and it is truly a process to meet the current needs of steel plates. Development of the controlled cooling technique has shown the possibility of using high strength steel under welding control similar to that for mild steel. It even encourages hopes for a quantitative demand increase in the range of high strength steel applications, and further inspires an expectation for an increased application of high strength steels centering on YP 36-

* Originally published in *Kawaski Steel Giho* 17(1985)1, pp. 60-67

Table 1 Chemical composition of YP 36 kgf/mm² steels used

Steel	Grade	Thickness (mm)	Chemical composition (wt %)									Remarks
			C	Si	Mn	P	S	Al	N (ppm)	C_{eq}*	P_{cm}**	
A 1	AH36	25	0.15	0.24	1.02	0.016	0.004	0.029	29	0.32	0.21	—
A 2		35										
B 1		14										
B 2	DH36	25	0.15	0.25	1.04	0.013	0.003	0.034	23	0.32	0.21	Modified with REM & Ti
B 3		35										
C 1		25	0.08	0.26	1.46	0.008	0.001	0.036	40	0.32	0.16	
C 2	EH36	35	0.09	0.24	1.48	0.006	0.002	0.023	43	0.34	0.17	
C 3		38	0.08	0.26	1.46	0.008	0.001	0.036	40	0.32	0.16	

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

** $P_{cm}=C+\frac{Si}{30}+\frac{Mn}{20}+\frac{Cu}{20}+\frac{Ni}{60}+\frac{Cr}{20}+\frac{Mo}{15}+\frac{V}{10}+5B$ (%)

kgf/mm² class which will take over the conventional YP 32-kgf/mm² class with its improved quality.

This paper reports on the base metal properties, and formability of the YP 36-kgf/mm² class hull structural steel plates, which have been manufactured by accelerated control cooling (ACC) of the multi-purpose accelerated cooling system (MACS) installed at Mizushima Works, together with the properties of the large heat input welded joint.

2 Sample Steel Plates

For sample steel, eight types of MACS-ACC-made YP 36-kgf/mm² class steel having different chemical compositions and plate thicknesses were used. **Table 1** shows chemical compositions, grades, thicknesses of respective sample steels. Steels A1 and A2 are AH 36 equivalent steels but not with REM and Ti addition to prevent deterioration of toughness at large heat input welded joints. Steels B1, B2 and B3 are DH 36 equivalent steels, while Steels C1, C2 and C3 are EH 36 equivalent steels, both subjected to the REM and Ti addition treatment for preventing toughness deterioration of the large heat input welded joint. For a contrast steel, the YP 36-kgf/mm² class hull structural steel was used which was made by Kawasaki Steel's Thermomechanical Rolling (KTR), which is a new controlled rolling process (non-water-cooled type).

Table 2 Mechanical properties of sample steels

Steel	Grade	Thickness (mm)	Tensile properties				Charpy V notch toughness		
			Direction	*YP* (kgf/mm²)	*TS* (kgf/mm²)	*El* (%)	Direction	$_vE_\theta$* (kgf·m)	CVN 50% FATT (°C)
A 1	AH36	25	T	38	52	27	L	27.0	−90
							T	22.1	−75
A 2	AH36	35	T	39	55	28	L	25.3	−55
							T	24.9	−57
B 1	DH36	14	T	39	53	26	L	25.2	−79
							T	18.8	−54
B 2	DH36	25	T	39	53	24	L	22.4	−76
							T	19.6	−66
B 3	DH36	35	T	42	55	24	L	24.5	−80
							T	21.9	−72
C 1	EH36	25	T	40	55	21	L	27.4	−99
							T	21.6	−97
C 2	EH36	35	T	41	55	20	L	29.8	−90
							T	26.5	−79
C 3	EH36	38	T	38	56	24	L	28.7	−115
							T	24.2	−99

* θ: Test temperature, AH36: 0°C, DH36: −20°C, EH36: −40°C

3 Base Metal Properties

3.1 Fundamental Properties of Base Metal

Table 2 shows the base metal tensile test results and 2-mm V-notch Charpy impact test results of sample steels. Base metal strength fully satisfies the requirements for *YP* 36-kgf/mm^2 or above and *TS* 50 kgf/mm^2 or above, and as far as strength is concerned, the MACS-ACC-made YP 36-kgf/mm^2 class steel (hereinafter called "MACS steel") is maintaining the same strength level as that of conventional controlloed rolling type steel (hereinafter referred to as "conventional steel"). The base metal toughness of MACS steel fully satisfies the rated value (3.5 kgf · m) at respectively specified test temperatures. Particularly, 50% FATT of AH and DH steels is −40°C or under both in L and T direction by the synergistic effect of refining the ferrite grain size in controlled rolling and inhibiting and ferrite grain growth by accelerated cooling, and is superior to the levels of conventional steels (−10°C to −30°C). **Figure 1** shows, in values of 50% FATT, the comparison in changes of toughness in the through-thickness direction of the sample steel at the 1-mm under-surface and the 1/2-*t* portion of the steel plate. The 1/2-*t* portion shows a slightly severer deterioration than the 1-mm under-surface, but the difference in 50% FATT is only within 20°C.

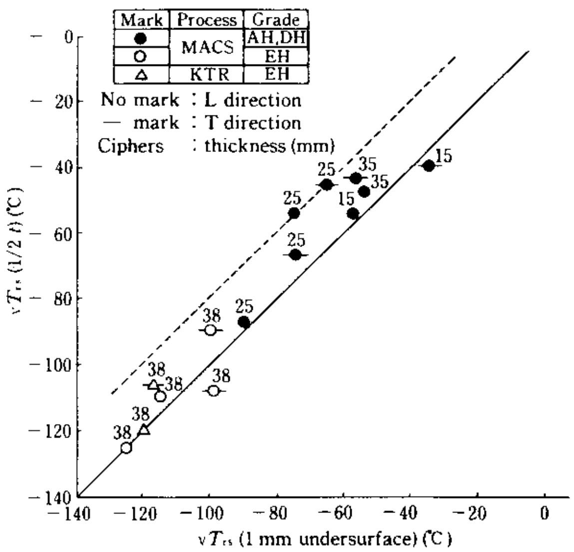


Fig. 1 Relation between $_vT_{rs}(1/2\ t)$ and $_vT_{rs}$ (1 mm under-surface)

Figure 2 shows the measured values of sample steel B3 (DH 36, 35 mm thick) as a typical example of through-thickness hardness distribution of sample steels. Change in hardness is 10 HV(10-kg load) at the maximum. This may be due to the fact that the grain size at the surface layer has become finer than that of the through-thickness center during controlled rolling, thereby lowering hardenability due to water cooling. This phenomenon constitutes one of the features of MACS steel for maintaining through-thickness homogeneity.

Photo 1 shows the microstructure of sample steels B2 and C1. The lamellar structure of ferrite and pearlite seen in the conventional steel of the controlled rolling type is not observed. Instead, a mixed structure of fine polygonal ferrite and bainite is obtained.[3)]

3.2 Low Temperature Weld Cracking Sensitivity

Regarding the weld zone, **Fig. 3** shows the results of the maximum hardness tests, and **Fig. 4** the results of the y-groove resistant cracking tests. The maximum hardness of MACS steel, corresponding to a decrease in the carbon equivalent, amounts to 260 HV or below even at a bead length of 50 mm, thereby revealing the higher safety of short beads in tack welding at site than that given by conventional steels.

In the y-groove resistant cracking test, the effect of lowering the carbon equivalent is also conspicuous, and the root crack preventing temperature is 0°C or below in all steel grades. This excellent weldability not only contributes to simplification of welding control, but also suggests the possibility of using non-low-hydrogen-based electrodes instead of conventional low-hydrogen-based electrodes[4)]

3.3 Fracture Toughness

Base metal fracture toughness was investigated by the COD test, deep notch test and ESSO test. The results

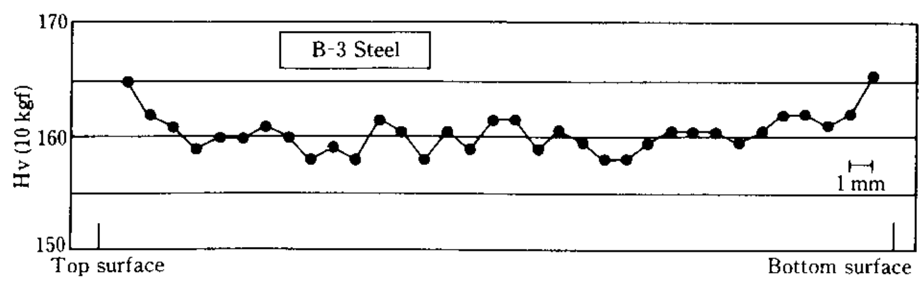
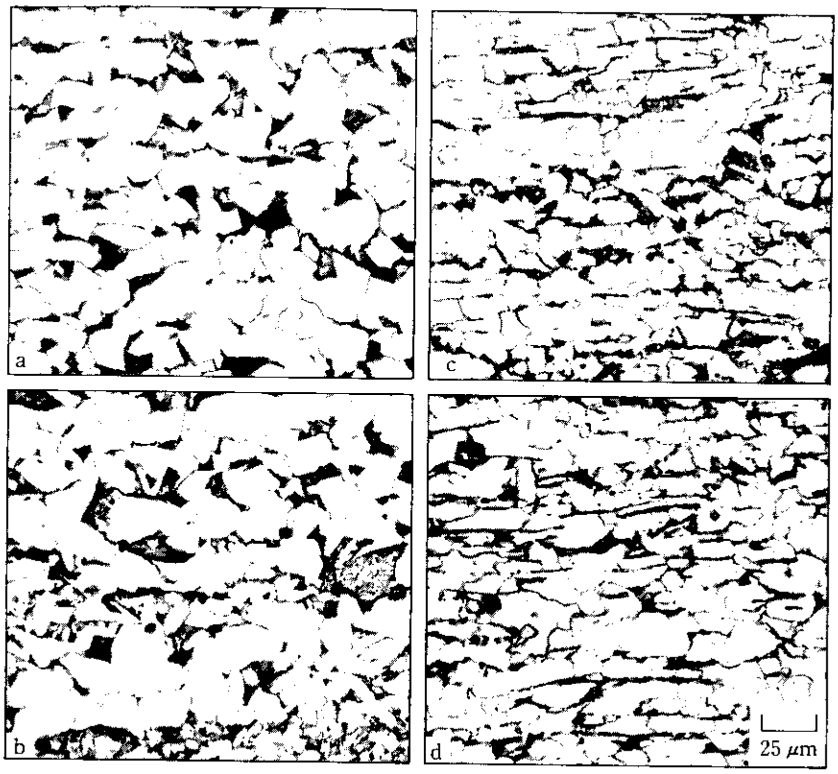


Fig. 2 Distribution of vickers hardness, HV(10 kg), on through-thickness direction.



a: B2 steel, 1/4*t*　　c: C1 steel, 1/4*t*
b: B2 steel, 1/2*t*　　d: C1 steel, 1/2*t*

Photo 1 Microstructures of B2 steel (DH36, $t = 25$ mm) and C1 steel (EH36, $t = 25$ mm)

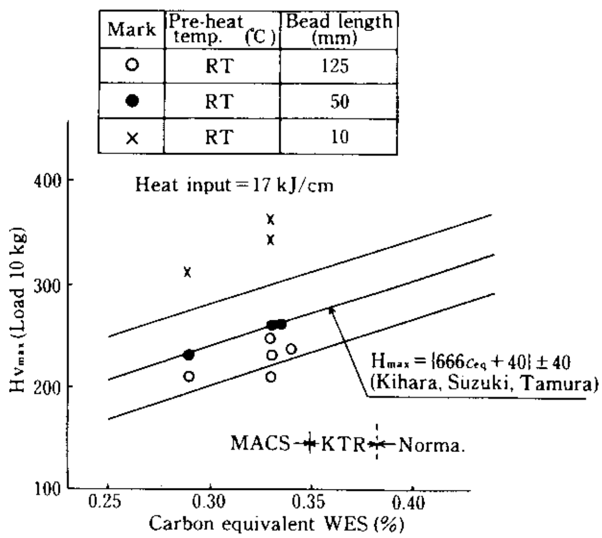


Fig. 3 Relation between maximum vickers hardness and carbon equivalent of MACS YP 36 kgf/mm^2 grade steels (plate thickness: 25–38 mm)

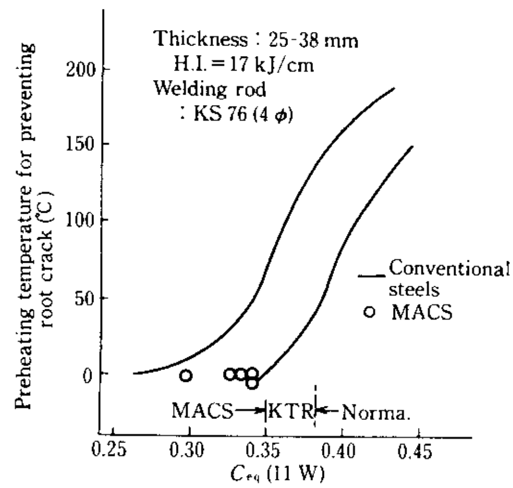


Fig. 4 Relation between C_{eq} and preheating temperature for preventing root crack in y-groove restriction cracking test

are shown in **Table.3**.

3.3.1 Brittle crack initiation toughness

Sample steels A1, A2, B2, B3, and C3 were sujected to L-direction and through-thickness (Z-direction) base-metal COD tests. As shown in Table 3, the test temperature at which the critical COD value (δ_C value) amounts to 0.2 mm, is −40 to −100°C in the L-direction and −47 to −72°C in the Z-direction for AH and DH class Steels (A1, A2, B2 and B3 steels), and −99°C in the L-direction and −51°C in the Z-

Table 3 Fracture toughness of base metal

Grade	Steel	Thick. (mm)	Longitudinal				Through thickness		
			COD		Deepnotch $K_C=200$ (°C)	ESSO $K_{ca}=600$ (°C)	COD		Deepnotch $K_C=200$ (°C)
			$\delta_C=0.1$ (°C)	$\delta_C=0.2$ (°C)			$\delta_C=0.1$ (°C)	$\delta_C=0.2$ (°C)	
AH36	A 1	25	<−100	−100	—	—	−87	−72	—
	A 2	35	−55	−40	—	—	−81	−54	—
DH36	B 2	25	−71	−73	−158	−1	−64	−47	—
	B 3	35	−84	−62	−150	—	—	—	—
EH36	C 3	38	−107	−99	−145	−48	−75	−51	−112

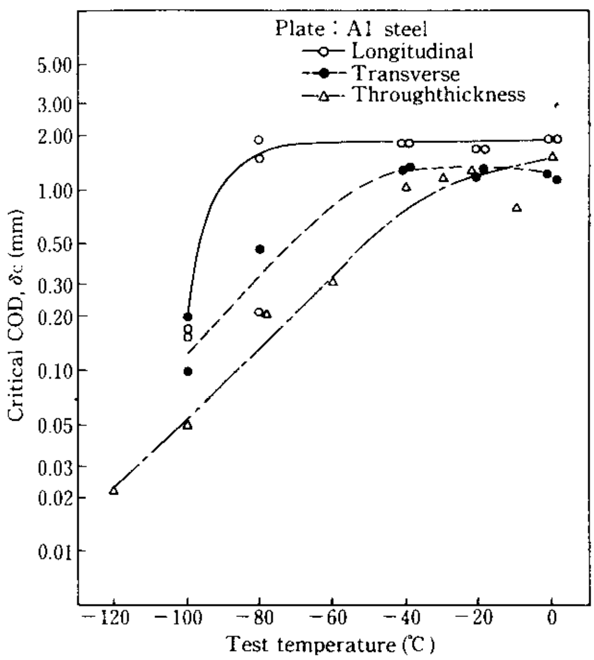


Fig. 5 Results of COD test (A1 steel: AH36, 25 mm)

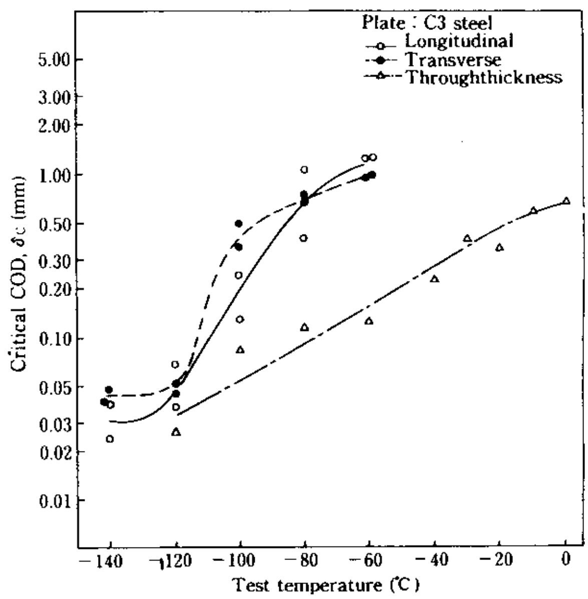


Fig. 6 Results of COD test (C3 steel; EH36, 38 mm)

direction for EH class steel (C3 steel). This shows that all these temperatures are on the safer side with respect to working tempratures. **Figures 5** and **6** show the dependence of δ_C value on temperatures in the L, T and Z directions of MACS-steel base metals for sample steels A1 and C3; **Fig. 7** shows the dependence of the fracture toughness value K_C on temperatures in the deep notch test for sample steels B2 and C3. The δ_C value for both A1 and C3 steels shows 0.3 mm or above in the L, T, and Z directions even at −40°C, and the temperature at which the K_C value shows 200 kgf/mm$^{3/2}$ is below −100°C in the Z-direction of C3 steel, which is fully on the safer side in terms of brittle crack initiation toughness.

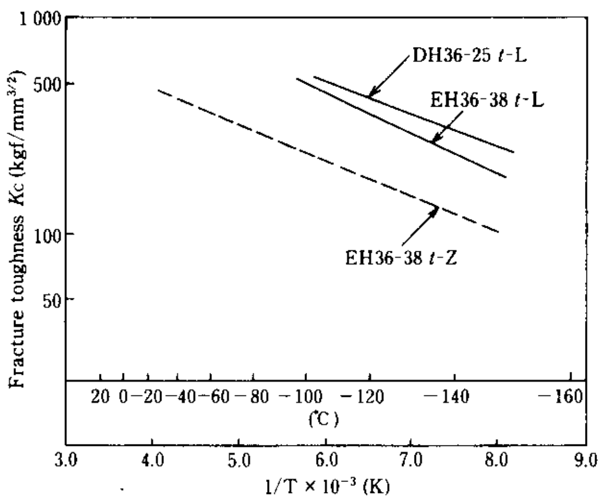


Fig. 7 Relation between fracture toughness K_C and test temperature of B2 (DH36 : 25 mm), and C3 (EH36 : 38 mm) steels

3.3.2 Crack arrest toughness

Figure 8 shows the dependence of the K_{ca} value on temperatures obtained by the ESSO test for sample steel C3. The temperature at which $K_{ca} = 600$ kgf/mm$^{3/2}$ is obtained is −48°C, which is fully on the safe side in terms of crack arrest toughness.

4 Properties of Welded Joint

One of the objectives of applying the ACC process is to improve the toughness of the high heat input welded joint. MACS steel is promising in improving the toughness of the high heat input welded joint and in enhancing welding efficiency due to its C_{eq} decrease effect, but softening of the welded joint and droping of its fatigue strength cause apprehension.[2,5] To confirm these points, various types of large heat input welded joints were made using MACS steel and their properties have been investigated.

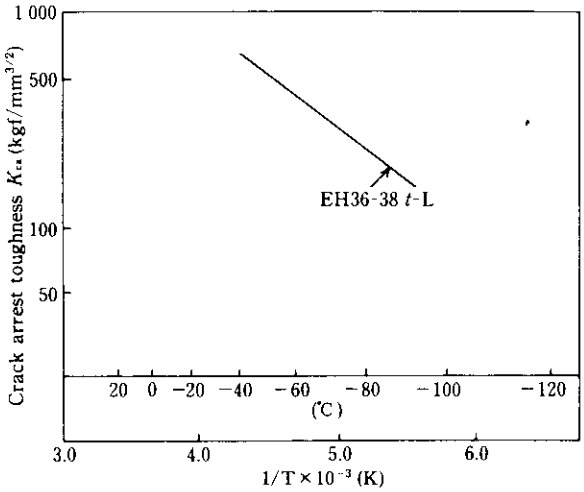


Fig. 8 Relation between crack arrest toughness K_{ca} and test temperature of C3 steel (EH35, 38 mm)

4.1 Welding Conditions

Welding methods used are one-side, one-pass submerged arc welding (FCB), electrogas welding (EGW) and electroslag welding (CESW). **Table 4** shows the welding conditions and the grades of steel welded.

Table 4 Welding conditions

Welding method	Steel	Groove Design	Pass No.	H.I. (kJ/cm)
EGW	A-1 AH36	10°, 25, 16	1	165
CESW	A-2 AH36	35, 25	1	637
SAW (FCB)	B-2 DH-36	25, 5	1	139
	B-3 DH-36 C-3 EH36	38 ~35, 5~6	1	265 ~ 270

4.2 Mechanical Properties of Welded Joint

Figure 9 shows the results of the tensile test and 2-mm V-notch Charpy impact test on the welded joints. In the welded joint tensile test employing NKU 2A test specimen, all sample steels satisfied their specifications. The results of the Charpy impact test also fully satisfied specified values at all required temperatures. **Figure 10** shows 2-mm V-notch Charpy transition curves at various positions of the welded joint on C3 steel (EH36).

Figure 11 shows a comparison between MACS steel and conventional steel in respect of the relation between the Charpy absorbed energy and weld heat input at the fusion line of the large heat imput welded joint. The absorbed energy of MACS lies on the upper side of the deviation range of the absorbed energy of conventional

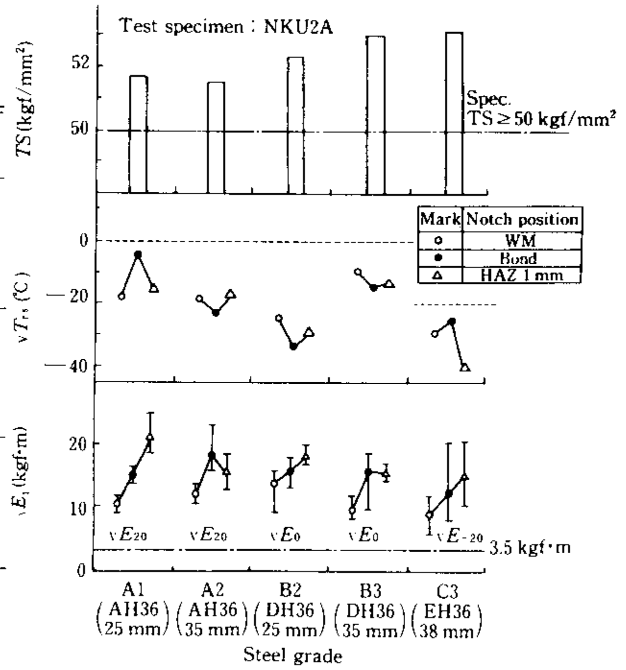


Fig. 9 Mechanical properties of weld joints

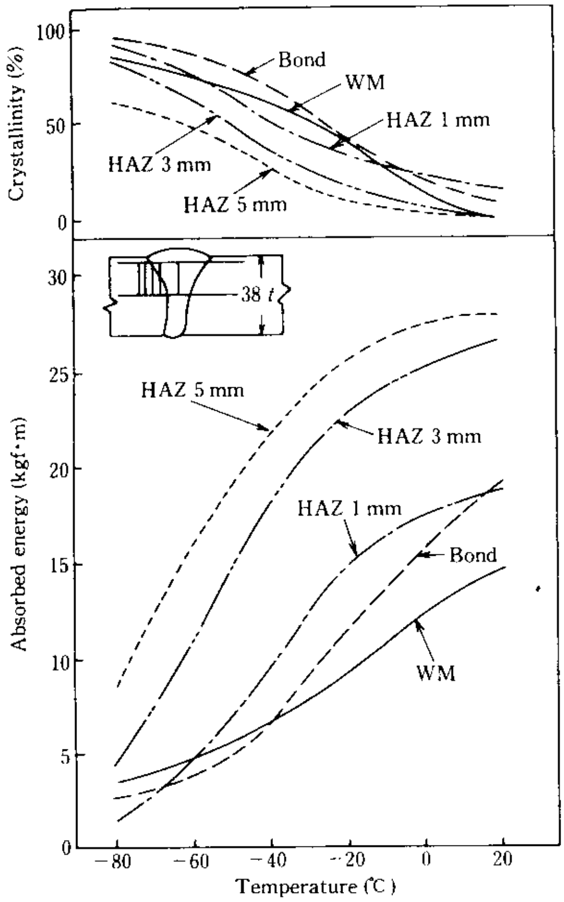


Fig. 10 Charpy impact properties of welded joint (C3 steel; EH36, 38 mm FCB)

steel, thereby indicating the effect of the C_{eq} decrease.

4.3 Fracture Toughness of Welded Joint

Table 5 is a summarization of the results of the Charpy impact test, COD test and deep notch test conducted on the fusion line and the 3 mm HAZ of the joint to investigate toughness and brittle crack initiation toughness of welded joints. The temperature at which the critical COD value indicates 0.1 mm on the welding

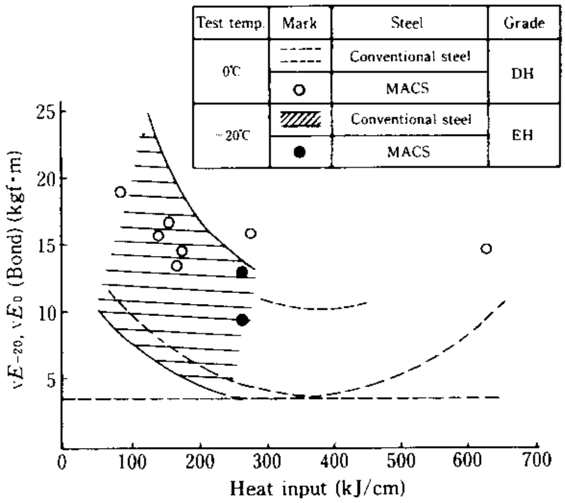


Fig. 11 Relation between $_vE_0$ (Bond) and heat input value

fusion line under the severest conditions, is −15°C for AH 36, −48°C and −50°C for DH 36 and −63°C for EH 36, which are all satisfactory. Moreover, the temperature at which K_C value (kgf/mm$^{2/3}$) indicates 400 on the fusion line in the deep notch test, is observed to be −23°C for DH 36 and −32°C for EH 36, thereby indicating that toughness at the fusion line of the large heat input welded joint of each steel grade is sufficiently on the safe side in terms of brittle crack initiation toughness. **Figure 12** shows C3 steel data as a typical example of the dependence of the ctitical COD value on temperatures at each joint, and **Fig. 13** shows that of the K_C value on temperatures at the joint fusion line for each sample steel.

4.4 Fatigue Strength of Welded Joint

Figure 14 shows fatigue test results using the weld joint and base metal of B3 steel (AH 36, 35 mm thick) which were subjected to CES welding with a heat input of 489 kJ/cm. For contrast data, the fatigue data of the 50 kgf/mm^2 steel joint by the National Research Insti-

Table 5 Fracture toughness of weld joints

Grade	Steel	Thick. (mm)	Welding method (H.I. kJ/cm)	Bond				HAZ 3 mm		
				$_vT_{rs}$ (°C)	COD $\delta_c=0.1$ (°C)	COD $\delta_c=0.2$ (°C)	Deep notch $K_C=400$ (°C)	$_vT_{rs}$ (°C)	COD $\delta_c=0.1$ (°C)	COD $\delta_c=0.2$ (°C)
AH36	A-1	25	EGW (165)	−6	−15	8	−5	−15	−80	−73
DH36	B-2	25	FCB (139)	−34	−48	−33	−23	−40	−52	−41
	B-3	35	FCB (270)	−15	−50	−37	—	−25	−59	−47
EH36	C-3	38	FCB (265)	−26	−63	−31	−32	−51	−75	−69

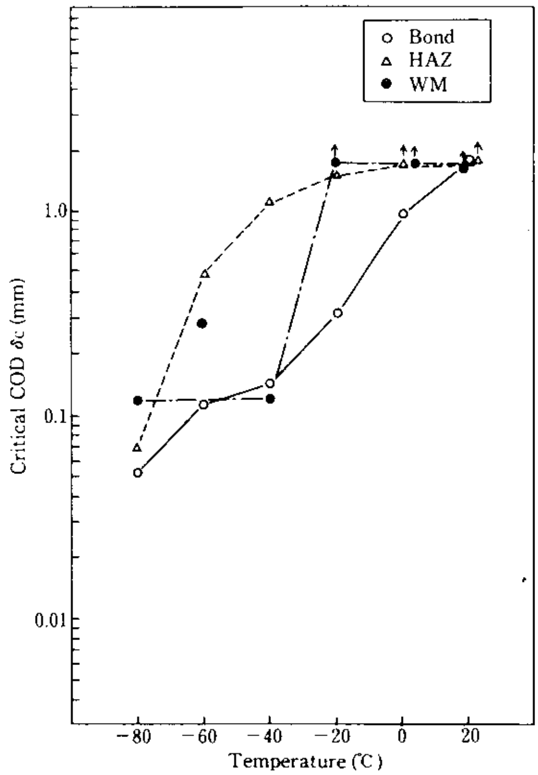


Fig. 12 Results of COD test of weld joint (C3 steel: EH36, 38 mm, FCB)

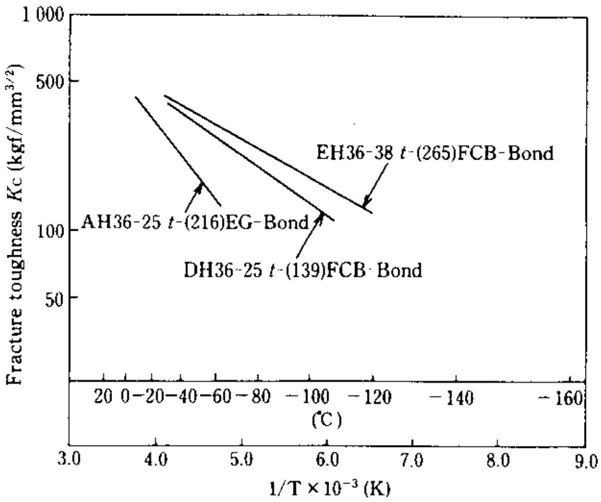


Fig. 13 Relation between fracture toughness K_C and test temperature of weld joint
(A1 steel: AH36 25 mm EGW)
(B2 steel: DH36 25 mm FCB)
(C3 steel: EH36 38 mm FCB)

tute for Metals were employed. The fatigue strength of MACS steel is approximately equal to that of the contrast data (non-water-cooled type SM50B) for base metal. For the welded joint, the fatigue strength lies at the upper limit of the fatigue strength deviation range of the contrast steel, thereby permitting the judgment that MACS steel maintains properties equal to those of conventional steels in terms of the fatigue strength of the weld joint.

5 Formability

To investigate the formability of MACS steel, the effect of the flame heating for forming—which is employed for hull structural steels—on toughness was investigated, in addition to a general pre-strain aging

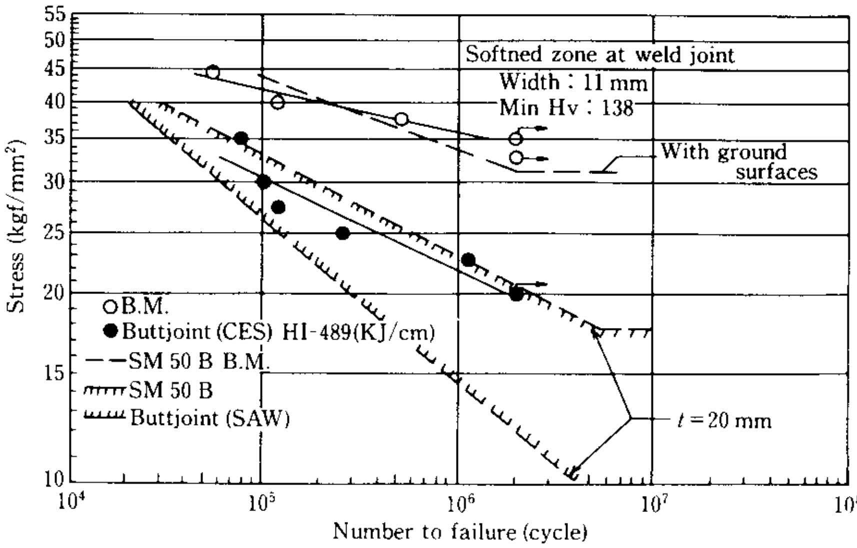


Fig. 14 Fatigue test results of base metal and weld joint of B3 steel (AH36, 35 mm)

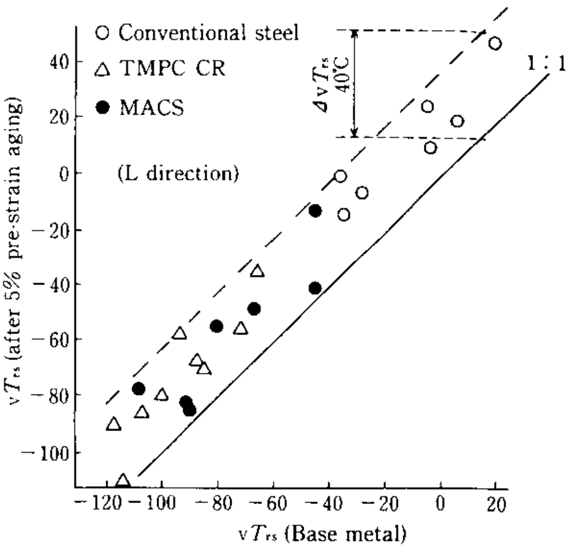


Fig. 15 Relation between $_{V}T_{rs}$ of base metals before and after 5% pre-strain aging treatment (250°C × 0.5~1h)

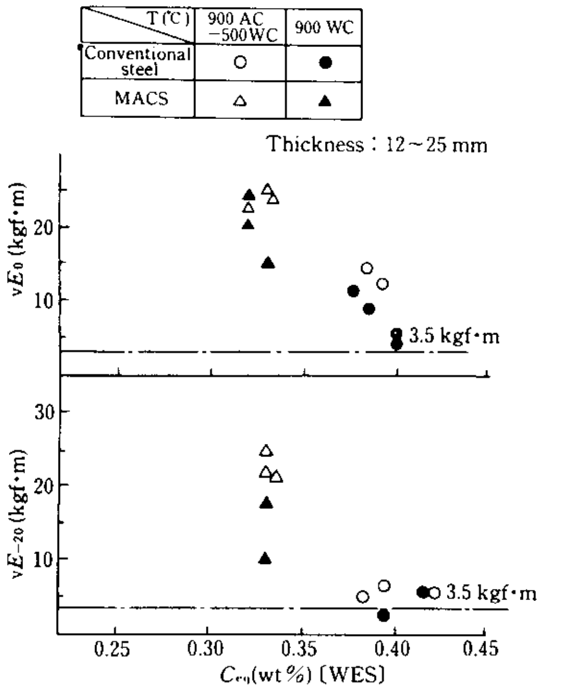


Fig. 16 Relation between C_{eq} WES and absorbed energy after flame heating (Grade: AH, DH)

test.

Figure 15 shows the Charpy transition curves of a 5% pre-strain aged (250°C × 0.5~1 h) MACS steel compared with that of conventional steels. The degree of deterioration in toughness by the pre-strain aging for both conventional steels and MACS steel lies within the range of transition temperatures of 0 to 40°C, thus being equal to each other.

Figure 16 shows the relation between Charpy absorbed energy after flame heating and the carbon equivalent. For the heating and cooling conditions, two methods stipulated by JSQS (Japan Shipbuilding Quality Standards) were selected, one being the method of air-cooling down to 500°C after heating up to 900°C and then water-cooling and the other being the method of water-cooling immediately after heating up to 900°C. Through its lower C_{eq} effect, MACS steel shows higher values than those by conventional steels in both methods mentioned above, and especially even in the method of water-cooling immediately after heating up to 900°C, MACS steel fully satisfies specified value, thereby inviting expectations for improvement in operational efficiency during actual work.[6)]

6 Manufacturing Records

Production of high strength hull structural steel plates manufactured by MACS exceeded 160 000 t in total from the commencement of commercial-process production from July 1983 to the end of February 1985 and at present their production reached the level of 10 000 to 20 000 t monthly. **Table 6** shows the breakdown by steel plate grade of manufacturing records from July 1983 to February 1985.

Table 6 Output of hull structural steel plate produced by MACS-ACC from Aug. '83 to Feb. '85

(t)

Grade \ YP	YP 32 kgf/mm²	YP 36 kgf/mm²	Total
AH, DH	143 150	19 386	162 536
EH	868	3 703	4 571
Total	144 018	23 089	167 107

Higher strength steels for hull structures manufactured by MACS are continuingly subjected to improvement in performance for special use represented by low-temperature specifications and heavy thick plates (over 100 mm thick) etc., in addition to various properties introduced in this report, and it is expected that through the results of the above improvements, further expansion in usage and production increase will be achieved in the future.

7 Concluding Remarks

The authors have reviewed the mechanical properties of high strength hull structural steel plates manufactured by MACS process which was set into operation in April 1983 at No. 2 plate mill of Mizushima Works.

The application of MACS process has made it possible to manufacture high strength heavy steel plates excellent in low-temperature welding crack sensitivity[7] and large heat input welded joint performance, with expectations for higher efficiency at actual construction, the simplification of construction work control, and the expansion of the scope of high strength steel applications.

References

1) K. Yamada, H. Yajima and K. Yasuda: *Bulletin of Soc. Naval Architects Japan*, No. 639(1982), 452.
2) T. Shiga: *Symposium for Application of TMCP Steel to Welded Structures*, Soc. Naval Architects Japan, (1983), pp. 117–147
3) T. Shiga, T. Hatomura, K. Amano and T. Enami: *Tetsu-to-Hagané*, **68**(1982)12, A227
4) Private communication
5) S. Takashima: *Symposium for Application of TMCP Steel to Welded Structure*, Soc. Naval Architects Japan, (1983), pp. 93–115
6) K. Yamada: *Symposium for Application of TMCP Steel to Welded Structure*, Soc. Naval Architects Japan, (1983), pp. 253–277
7) Y. Kusuhara, E. Kobayashi, F. Ohnishi, I. Hirai, K. Amano, and R. Tarui: *Kawasaki Steel Technical Report*, No. 13(1985), 77