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Properties of 390- and 415-MPa Yield Strength Steel Plates with Good Toughness in Large Heat Input Welded Joints*


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Synopsis:

Ship structural 390 MPa yield strength (YP 40 kgf/mm^2) steels and an offshore structural 415 MPa yield strength (YP 42 kgf/mm^2) steel were developed to assure good low temperature toughness in large heat input welded joints. They were produced using MACS (Multipurpose accelerated cooling system) with low N and a small amount of Nb and REM-Ti addition for the YP 390 MPa steels and with low C, medium Mn, low N, and small amounts of Nb and REM-Ti addition for the YP 415 MPa steel. Tensile, Charpy impact and fracture mechanics tests proved that the steel plates and their welded joints made by electro-gas welding and one-side one-pass submerged arc welding with heat inputs of 147 to 274 kJ/cm had sufficient properties for ship and offshore structures.

1 Introduction

High strength steel plates have long been used in constructing merchant ships in Japan. Their application to ship building was to reduce the weight of ship structures, and this enabled the construction of the so-called "energysaving ships" aimed at reducing fuel consumption. The yield strength of ship structural steel has increased from 315 MPa to 355 MPa. The high strength steel occupies as much as 50 to 75% of the total weight of steel structure of a 50 000-t and higher class ship. This trend owes much to the progress in techniques of both steel plate making and ship designing. One of the most important progresses in steel plate making techniques is the invention of thermo-mechanical control process (TMCP). The TMCP enables the production of high strength steel plates with good weldability. The recent trend of adding more value to products promotes the use of high strength steels with higher yield strength. The steel which assures the yield strength of 390 MPa, YP390-MPa steel, is one of such examples.

In the field of offshore structures, on the other hand, the application of high strength steel plates to mobile rigs such as semi-submersible rigs and caisson rigs is also sought to reduce machinery transportation costs through an increase in loading capacity. The steel which assures the yield strength of 415 MPa, YP415-MPa steel, is such an example.

These steel plates can be used more effectively in the combination of large heat input welding, which must be taken into account in steel developments.

The present paper describes the development and characteristics of YP390-MPa and YP415-MPa steel plates for large heat input welding.

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2 Aimed Properties of Steel Plates Developed

Table 1 lists the aimed properties of the steel plates developed in both directions parallel and normal to the major rolling direction. The aimed strength of the YP390-MPa steel plate was determined according to the NV rule, while that of the YP415-MPa was determined based on the ASTM A537 Class 2. The toughness of the YP390-MPa steel plate and its one-side one-pass submerged arc welded joint was aimed to be not lower than that of YP360-MPa steel plate, while that of the YP415-MPa steel plate and its one-side one-pass submerged arc welded joint was designed to be satisfied at −60°C. Both plates were also made to be weldable at 0°C without any preheating.

Table 1 Aimed properties of steel plates and their welded joints

Steel		Plate thickness (mm)	Steel plate: Tensile test YP (MPa)	Steel plate: Tensile test TS (MPa)	Steel plate: Charpy test 50% FATT (°C)	Welded joint: Welding method	Welded joint: Charpy test Temp. (°C)	Welded joint: Charpy test Absorbed energy (J)	Preheating temperature for preventing weld cracking (°C)
YP 40 kgf/mm² (YP 390 MPa)	A	25	≧390	≧530	≦−40	EG	0	≧39	≦0
		30				One side SAW			
	E	25	≧390	≧530	≦−60	One side SAW	−20	≧39	
YP 42 kgf/mm² (YP 415 MPa)	—	30	≧415	≧550	≦−80	One side SAW	−60	≧39	
						EG			

3 Metallurgical Approach

Table 2 lists metallurgical approach for producing plates which should fulfill the above-mentioned aimed properties. In order to assure high toughness of large heat input welded joints, metallurgical improvements such as reduction of carbon equivalent and nitrogen and addition of rare earth (REM) and Ti were made.

Table 2 Metallurgical approach for improving HAZ toughness of large heat input welded joint

Item	Improvement of HAZ toughness: Metallurgy	Improvement of HAZ toughness: Approach
Grain size	Grain boundary pinning effect of insoluble fine precipitate	· Fine dispersion of TiN · REM addition
Micro-structure	Reduction of M-A constituent in upper bainite structure	· Lowering C_{eq} · Lowering C · Lowering N → Compensation of strength → · MACS process / · Use of Nb and/or Cu-Ni
	Nucleation of fine ferrite-pearlite structure	· Lowering Ceq · REM addition
Matrix	Reduction of free N and sol. Ti	· Lowering N · Control of Ti/N

The addition of REM and Ti is made so that REM-oxysulfides and TiN can control the coarsening of austenite grains. **Figures 1**[1] and **2** show the effect of REM and Ti addition on the coarsening of austenite grains. Figure 1 indicates that the more the TiN smaller than 0.04 μm exists, the smaller the austenite grains are. The REM in the form of stable fine particles of REM-oxysulfide, on the other hand, is expected to replace TiN, as shown in Fig. 2, to prevent the coarsening of austenite grains near fusion line where TiN tends to dis-

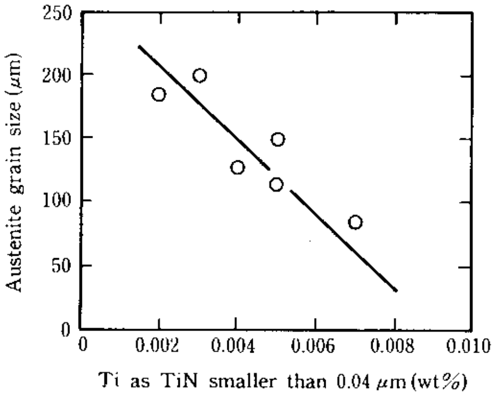


Fig. 1 Relation between austenite grain size at 1 350°C and Ti content as TiN smaller than 0.04 μm existing in the plate before welding

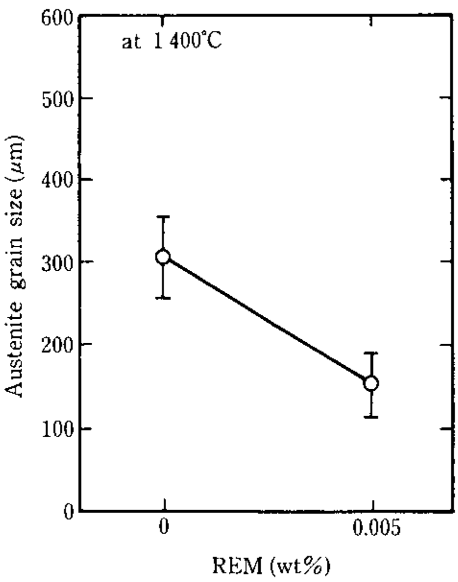


Fig. 2 Effect of REM content on austenite grain size at 1 400°C (0.13%C-0.25%Mn-0.015%P-0.004%S-0.02%Al-0.014%Ti)

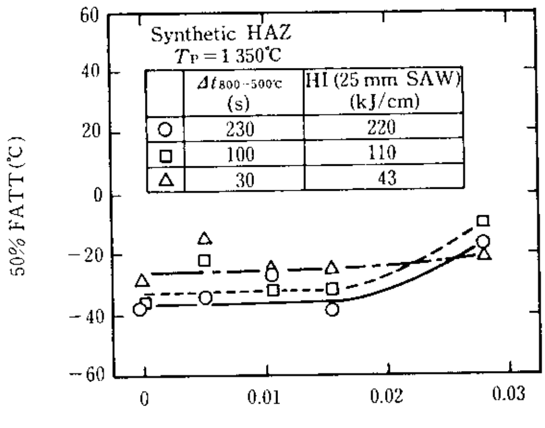


Fig. 3 Effect of Nb content on the synthetic HAZ toughness

solve. REM-oxysulfides are also expected to prevent the formation of crude upper bainite by acting as ferrite nuclei.

The reduction of carbon equivalent lowers the preheating temperature which is required to prevent weld cracking. The reduction of nitrogen improves toughness of heat-affected zone (HAZ) of welded joint by controlling nitrogen in solid solution and formation of martensite-austenite constituents. The decrease in strength due to reduction of carbon equivalent and nitrogen, on the other hand, was compensated by the addition of Nb for YP390-MPa steel and Nb, Cu and Ni for YP415-MPa steel and also by the use of thermomechanical process (MACS–Multipurpose Accelerated Cooling System). Though the addition of Nb is effective in increasing strength of base metal, too much addition deteriorates the HAZ toughness of large heat input welded joints. **Figure 3** shows the effect of Nb on toughness of simulated HAZ. The figure indicates that the addition of Nb not more than 0.02% does not significantly affect the HAZ toughness of large heat input welded joint. The Cu and Ni were added as the elements which increase strength without deteriorating HAZ toughness.

4 Properties of YP390-MPa and YP415-MPa Steel Plates

4.1 Steel Plates

The chemical compositions of the steels are listed in **Table 3**. The ratio of C to Mn (C/Mn ratio) was 0.13 and 0.06 for YP390-MPa steel grade A and grade E, respectively, while that of YP415-MPa steel was 0.05. The contents of N, S, and P were controlled at low levels, with Nb in small quantity and REM-Ti added. The carbon equivalent was 0.34% and 0.31% for YP390-MPa and YP415-MPa steels, respectively. The steel was refined in basic oxygen furnace, degassed and continuously cast into slabs which were then controlled-rolled before accelerated cooling by MACS.

4.2 Basic Properties of Steel Plates

Table 4 summarizes the tensile properties and 2-mm V-notched Charpy test results of the steel plates. All the plates thoroughly satisfied the aimed strength and toughness listed in Table 1. The reduction of area in through-thickness direction was more than 70%, indicating that the plates have good anti-lamellar tearing properties.

The microstructures of steel plates are shown in **Photo 1**. They are fine structures mainly consisting of ferrite and bainite.

The brittle fracture initiation properties of the plates were studied by the three-point bend CTOD test and the center-notched, wide plate tensile test (deep notch test). The values of CTOD exceeded 1.8 mm at 0°C for YP390-MPa grade-A steel plate, 1.9 mm at −60°C for grade-E plate and 1.3 mm at −60°C for YP415-MPa steel plate. The deep notch test indicates that YP390-MPa grades A and E and YP415-MPa steel plates do not fracture at temperatures higher than −135°, −152°, and −145°C, respectively, even though each plate having an

Table 3 Chemical compositions of steel plates (wt %)

Steel		C	Si	Mn	P	S	Al	Nb	Cu	Ni	N	C_{eq}^{*}	P_{cm}^{**}	Note
YP 40 kgf/mm² (YP 390 MPa)	A	0.14	0.33	1.20	0.013	0.002	0.031	0.014	—	—	0.0031	0.34	0.211	REM-Ti treated
	E	0.10	0.33	1.43	0.012	0.002	0.033	0.015	—	—	0.0036	0.34	0.183	
YP 42 kgf/mm² (YP 415 MPa)	—	0.07	0.22	1.35	0.009	0.002	0.028	0.017	0.14	0.13	0.0027	0.31	0.154	

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

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

Table 4 Mechanical properties of steel plates

Steel		Plate thickness (mm)	Direction	Location	Tensile test*				Charpy impact test			
					YP (MPa)	TS (MPa)	El (%)	RA (%)	Absorbed energy (J) −40°C	−60°C	−80°C	50% FATT (°C)
YP 40 kgf/mm² (YP 390 MPa)	A	25	L	1/4 t	441	569	30	76	248	219	74	−67
				1/2 t	436	569	30	75	215	153	72	−64
			C	1/4 t	461	579	26	72	184	171	34	−66
				1/2 t	456	579	25	71	140	79	33	−46
			Z	1/2 t	446	574	45	75				
		30	L	1/4 t	436	564	30	76	262	195	129	−73
				1/2 t	446	564	29	76	168	113	47	−52
			C	1/4 t	456	569	28	75	194	171	123	−76
				1/2 t	446	569	28	73	142	103	30	−46
			Z	1/2 t	451	574	55	73				
	E	25	L	1/4 t	441	549	31	77	314	297	302	−113
				1/2 t	441	549	30	75	322	306	238	−97
			C	1/4 t	451	554	28	75	303	286	227	−103
				1/2 t	451	549	29	74	279	233	184	−93
			Z	1/2 t	456	559	54	74				
YP 42 kgf/mm² (YP 415 MPa)	—	30	L	1/4 t	451	564	27	77	321	308	293	−114
				1/2 t	451	559	27	75	318	298	272	−105
			C	1/4 t	481	569	26	73	245	208	171	−100
				1/2 t	470	559	26	74	230	200	149	−87
			Z	1/2 t	451	569	53	75				

* Specimens: "NKU14A" for L and C
10 mmϕ, GL=20 mm for Z

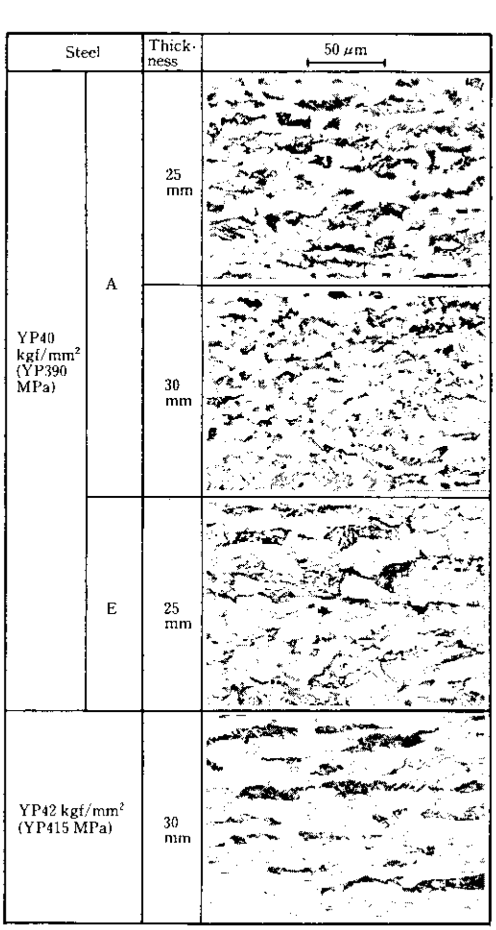


Photo 1 Microstructure of plates tested

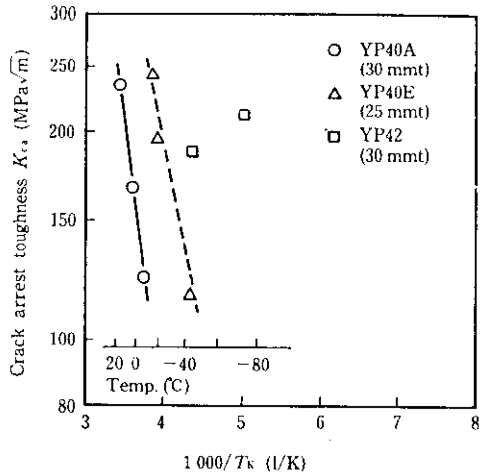


Fig. 4 Plot of crack arrest toughness vs. temperature

80 mm long through-thickness crack is subjected to a stress as large as a half of the specified yield strength.

Figure 4 shows the crack arrest toughness of the plates evaluated by the double tension test. The temperature for the crack arrest toughness of 186 MPa$\sqrt{m}$, which is a criterion made on the basis of effective stress intensity factor during crack propagation,[2)] was −25° and −65°C for YP390-MPa grade-E and YP415-MPa steel plates, respectively.

4.3 Weldability

4.3.1 Maximum hardness test

Table 5 shows the maximum hardness test results. The test was performed according to JIS Z3101 (Testing Method of Maximum Hardness in Weld Heat-affected Zone) at the atomospheric temperature of 0°C for bead lengths of 10, 50, and 125 mm. The result indicates that the maximum hardness is as large as that for the water-cooled-type YP350-MPa steel plate.

4.3.2 Weld cracking susceptibility

The susceptibility of the plates to weld cracking was studied by the Y-groove cracking test (JIS Z3158). No

Table 5 Maximum hardness test results (HV)

Steel		Plate thickness (mm) \ Bead length (mm)	10	50	125
YP 40 kgf/mm² (YP 390 MPa)	A	30	320	288	265
	E	25	309	258	248
YP 42 kgf/mm² (YP 415 MPa)	—	30	328	308	293

crack was observed in all the plates tested at 0°C, indicating that the temperature for preventing root cracking is lower than 0°C.

4.4 Strain Aging Properties

The strain aging properties of the plates were studied by aging them at 250°C for 30 min after applying strain of 5%. **Table 6** summarizes the results. The change in fracture appearance transition temperatures induced by strain aging ranged between 8° and 31°C, which are on the same level as YP350-MPa steel plates.

Table 6 Effect of strain aging on Charpy impact test result

Steel		Plate thickness (mm)	Strain aging*	Charpy impact test: Absorbed energy (J) −40°C	−60°C	50% FATT (°C)	ΔT** (°C)
YP 40 kgf/mm² (YP 390 MPa)	A	25	No	184	171	−66	−25
		25	Yes	124	58	−41	
		30	No	194	171	−76	−8
		30	Yes	187	148	−68	
	E	25	No	303	286	−103	−31
		25	Yes	187	100	−72	
YP 42 kgf/mm² (YP 415 MPa)	—	30	No	245	208	−100	−29
		30	Yes	230	159	−71	

* Strain aging: 5% +250°C × 30 min

** ΔT = (50%FATT of nonstrain aged material) − (50%FATT of strain aged material)

4.5 Properties of Large Heat Input Welded Joints

4.5.1 Welding conditions

Table 7 lists the welding conditions. The one-side one-pass welding was performed by submerged arc welding with two and three electrodes and by electrogas arc welding with one electrode. The heat input ranged between 147 and 274 kJ/cm.

4.5.2 Tensile properties

Table 8 summarizes the tensile test results of welded joints and HAZ. The tensile test of HAZ was carried out with round bar specimens of 6 mm in diameter, which were taken parallel to the weld bead. Though the strength of HAZ did not exceed the aimed tensile strength of the plate, the welded joint did. This result indicates that the welded joint as a whole has sufficient strength so that it can be used in practice without any problem.

Table 7 Welding conditions

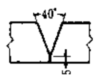
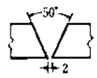
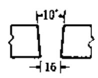
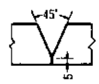
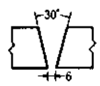
Steel		Plate thickness (mm)	Welding method	Groove shape (mm)	Electrode	Cur. (A)	Volt. (V)	Speed (cm/min)	Heat input (kJ/cm)
YP 40 kgf/mm² (YP 390 MPa)	A	30	One side SAW		L	1 500	35	60	166
					T1	1 400	40		
					T2	1 150	50		
	A	25	EG		—	580 ~ 590	30 ~ 31	4	261 ~ 274
	E	25	One side SAW		L	1 080	32	26	149
					T	750	40		
YP 42 kgf/mm² (YP 415 MPa)	—	30	One side SAW		L	1 300	35	43	202
					T1	1 050	40		
					T2	1 150	50		
			EG		—	340 ~ 350	36 ~ 38	5	147 ~ 160

Table 8 Tensile strength of welded joints

Steel		Plate thickness (mm)	Welding method	Tensile strength (MPa): Welded joint*	HAZ**
YP 40 kgf/mm² (YP 390 MPa)	A	25	EG	574	549
		30	One side SAW	574	544
	E	25	One side SAW	534	526
YP 42 kgf/mm² (YP 415 MPa)	—	30	One side SAW	569	522
		30	EG	559	533

* Specimens for welded joint: NKU2A

** Specimens for HAZ: 6 mmϕ round bar

4.5.3 Charpy impact test

Figure 5 summarizes the Charpy impact absorbed energy at various positions of the welded joints. They exceeded 50 J at 0°C for YP390-MPa grade-A steel, 60 J at −20°C for YP390-MPa grade-E, and 39 J at −60°C for YP415-MPa. These values are larger than the aimed ones for the steel plates.

4.5.4 CTOD properties

The CTOD test was performed with the welded joints made according to actual procedures of large heat input welding, because it was difficult in large heat input welded joint to make a straight fusion line as in the multi-pass welded joint used in the weldability test of off-

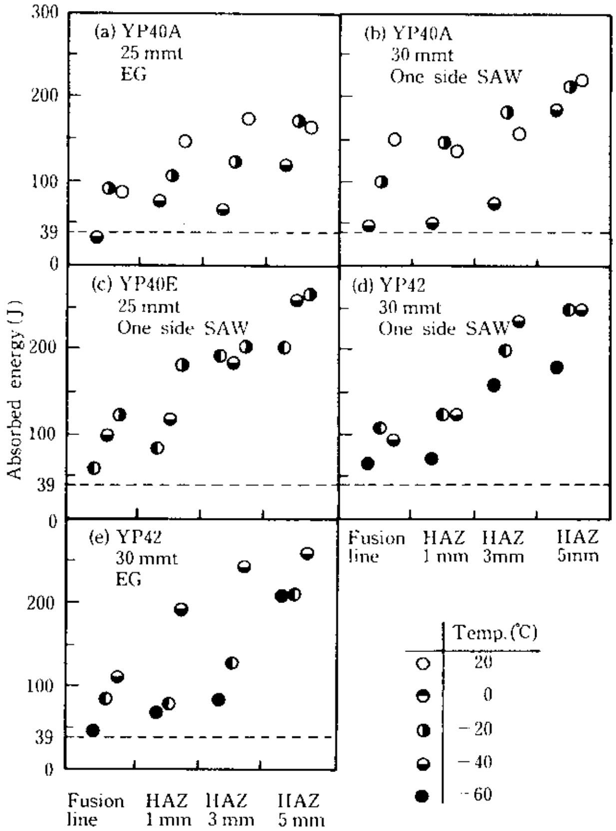


Fig. 5 Charpy impact energies of welded joints (Specimens were cut from 1 mm below the plate surface)

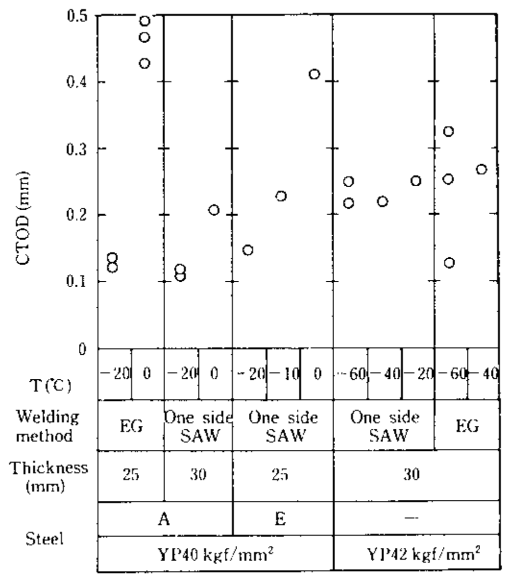


Fig. 6 CTOD values of the welded joints at fusion line

shore structural steel plates. **Figure 6** summarizes CTOD values for fusion lines.

Though the CTOD value required for the welded joint is still to be decided, API[3] has stipulated 0.25 mm for the welded joint of offshore structural steel plate not thicker than 75 mm. If this criterion is adopted, all the welded joints of YP390-MPa steel plate can be used at 0°C, the one-side one-pass submerged arc welded joint at −20°C, and the electrogas arc welded joint at −40°C. Since API specification does not provide any structural conditions, however, it does not seem to have thorough ground from the viewpoint of fracture mechanics.

When CTOD is applied to safety assessment of offshore structures, CTOD design curves are used. So far, BSI PD6493[4] and WES2805[5] have presented their own CTOD design curves. Though some problems have been pointed out concerning the CTOD design curves,[6] let us use the design curve presented by WES2805 whose validity has been examined by the test using notched wide-plate tensile test specimens and welded joint specimens with surface notches at toes. If the idea used in ASME Boiler and Pressure Vessel Code Sec. III[7] is adopted, then a surface defect whose depth is 1/4 of the thickness and whose length is 6 times as large as the depth may be assumed. Suppose that the plate thickness is 30 mm. Then, the effective defect size parameter is 8.1 mm which agrees the value assumed by Pisarski, et al.[8] Since the applied strain e is determined by the configurations of structure and design stress, a structure, which has a surface defect parallel to the bead of the welded joint with angular distortion of 15 mm/1000 mm and offset of 5 mm and is normally subjected to a tensile stress as large as half of the specified strength e_Y, is assumed. Then the total strain applied to such a welded joint becomes $1.7e_Y$.

These assumptions require a CTOD value of 0.1 mm to the welded joints of YP390-MPa and YP415-MPa steel plates when they are used in ordinary conditions. The large heat input welded joint can be used at −20°C for the YP390-MPa steel plate and at −60°C for the YP415-MPa steel plate.

4.5.5 Center-notched wide-plate tensile test

The center-notched wide-plate tensile test was performed using specimens, each of which had a through-thickness notch in the weld bond. **Figure 7** plots the fracture toughness calculated from the fracture stress vs. temperature. The fracture toughness exceeded 155 MPa$\sqrt{m}$ at 0°C except for the one-side one-pass submerged arc welded joint of YP390-MPa grade-A steel. The figure also plots the data of another YP390-MPa grade-A steel whose C and Mn contents are 0.11% and 1.42%, respectively.

4.6 Fatigue Properties

The fatigue properties of 25 mm thick YP390-MPa grade-A and YP415-MPa steel plates were studied using

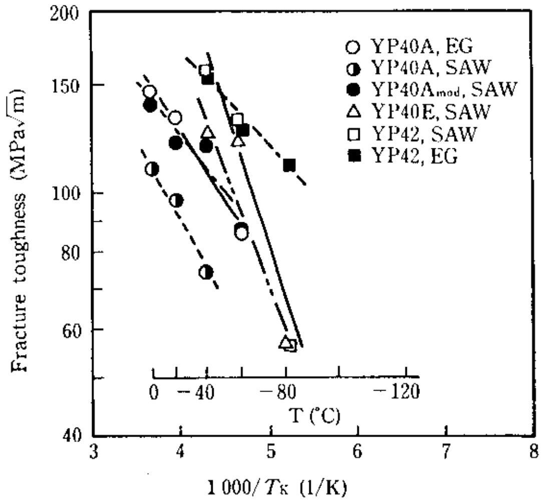


Fig. 7 Plot of fracture toughness of welded joints vs. temperature

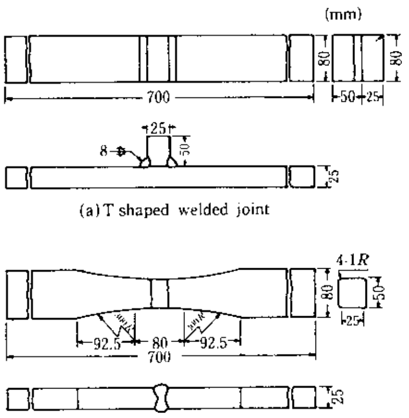


Fig. 8 Specimen geometries for fatigue test

Table 9 Fatigue strength of steel plates and their welded joints

	Fatigue strength* (MPa)	
	YP 40 kgf/mm² (YP 390 MPa)	YP 42 kgf/mm² (YP 415 MPa)
Base metal	361	397
T-shaped welded joint	115	122
Butt welded joint	142	138

* Defined by the stress range which gives the life of 2 × 10⁶ cycles

specimens of plates, T-shaped welded joints made by shielded metal arc welding and butt-welded joints made by CO_2 gas welding. The specimen geometries of the welded joints are shown in **Fig. 8**. The fatigue test was performed in zero-tension. **Table 9** lists the fatigue strength for 2×10^6 cycles, which is on the same level as the YP350-MPa steel.

5 Conclusions

The steel plates for large heat input welding, which had been developed as YP390-MPa steel for ship hull structures and YP415-MPa steel for offshore structures were produced by MACS process. Their properties were studied using welded joints made by the electrogas arc welding and the one-side one-pass submerged arc welding with heat input ranging between 147 and 274 kJ/cm. The main results obtained follow:

(1) YP390-MPa steel
- (a) The low-N steel plate with a small amount of Nb and REM-Ti added had higher strength and toughness than aimed.
- (b) The large heat input welded joints gave higher strength than aimed for plate and Charpy absorbed energies of more than 50 J at 0°C for grade-A steel and more than 60 J at −20°C for grade-E steel. The CTOD value was higher than 0.25 mm at 0°C.

(2) YP415-MPa steel
- (a) The low-C, medium-Mn, and low-N steel plate with a small amount of Nb, Cu-Ni, and REM-Ti added had higher strength and toughness than aimed.
- (b) The large heat input welded joints gave higher strength than aimed for plate and Charpy absorbed energy of more than 39 J at −60°C. The CTOD value exceeded 0.25 mm at −20°C for the one-side one-pass submerged arc welding and at −40°C for the electrogas arc welding.

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