KAWASAKI STEEL TECHNICAL REPORT

No.20 (June 1989)

Information Systems

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Keniti Amano, Osamu Tanigawa, Chiaki Shiga, Taketo Okumura

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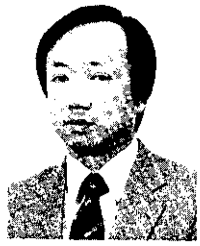
Development of Controlled-Rolled 70 kgf/mm^2 and 80 kgf/mm^2 Class High Tensile Strength Steel Plates for Welded Structures*


Keniti Amano
Dr. Engi., Senior Researcher, Plates, Shapes & Castings Lab., Heavy Steel Products Research Dept., I & S Research Labs.


Osamu Tanigawa
Staff Deputy Manager, Plate, Casting & Forging Control Sec., Technical Control Dept., Mizushima Works


Chiaki Shiga
Dr. Engi., Chief of Joining & Physical Metallurgy Lab., Heavy Steel Products Research Dept., I & S Research Labs.


Taketo Okumura
Staff Manager, Planning Sec., Planning Dept., Mizushima Works

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1 Introduction

In recent years, the trend in construction equipment has been toward simultaneous weight reduction and increased size, and toward higher fabrication efficiency. Steels used in this field must, therefore, meet increasingly severe strength, toughness, cold formability, weldability, thickness, and economy requirements. Non-quench-tempered high tensile strength steels with a tensile strength (TS) of up to 60 kgf/mm^2 (588 MPa) in the as-plate-rolled condition are commonly used in construction equipment. Also, those with TS of 80 kgf/mm^2 (784 MPa) have been developed as materials for as-hot-rolled sheets with thicknesses up to about 8 mm[1-7].

To increase the strength and thickness of these conventional steels without sacrificing the formability and weldability of the conventional steels, an investigation was made into as-plate-rolled, i.e., non-quench-tempered high tensile steel plates HT 70 and HT 80.

This report first describes results of a fundamental examination for development and then discusses the properties of the steels developed.

2 Fundamental Examination

2.1 Concept of Development

If expensive elements such as Ni and Mo are not to

* Originally published in *Kawasaki Steel Giho*, 21(1989)1, pp. 19-25

Table 1 Chemical compositions of steels

(wt. %)

Steel	C	Si	Mn	P	S	Al	Nb	Ti	N	C_{eq}*1	P_{cm}*2
1	0.10	0.24	1.79	0.015	0.003	0.042	0.039	0.14	0.007	0.40	0.198
2	0.10	0.25	1.80	0.013	0.005	0.038	0.041	0.005	0.004	0.40	0.196

*1 $C_{eq}=C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15$
*2 $P_{cm}=C+Si/30+(Mn+Cu+Cr)/20+Mo/15+V/10+Ni/60+5B$

be used for reasons of economy, it is very difficult to produce as-plate-rolled HT 70 and HT 80 heavy-gauge steel plates. A basic concept is the combined utilization of precipitation hardening, transformation strengthening, solid solution strengthening, grain refinement strengthening, and dislocation hardening. For as-hot-rolled HT 80[2)] steel sheet, TiC precipitation hardening is the principal strengthening mechanism, and transformation strengthening and solid solution strengthening are employed in combination. In plate rolling where heavy rolling at low temperature is possible, full use is made of the effects of grain refinement strengthening and dislocation hardening by rolling in the ferrite (α) plus austenite (γ) dual-phase region. Moreover, it can also be expected that the effect of precipitation hardening by the strain-induced precipitation of TiC in the α region will increase due to dual-phase region rolling.

2.2 Experimental Procedure

The chemical compositions of the test steels are given in **Table 1**. Steel 1 is an as-hot-rolled non-quench-tempered HT 80 steel sheet and provides TS $\geqq$ 80 kgf/mm^2 with a thickness of 4.5 mm in the as-hot-rolled condition. Steel 2 is a laboratory-melted comparison steel to which Ti was not added. Reheating and rolling conditions of slabs made of these steels were examined using a laboratory mill. Slabs 110 mm in thickness were cut from these mother slabs for test rolling, and 13-mm thick plates were produced at varying reheating temperatures between 1 050°C and 1 300°C and finish-rolling temperatures between 500°C and 840°C; air cooling was conducted after rolling.

The tensile test and Charpy impact test were conducted on test specimens taken from rolled plates in both the longitudinal and transverse directions relative to the rolling direction. Microstructures were observed using optical and electron microscopes.

2.3 Results of Experiments and Discussion

2.3.1 Relationship between slab reheating conditions and mechanical properties

The effect of slab-reheating temperature on the strength and toughness of steel 1 is shown in **Fig. 1**. In the steel plates rolled at finishing temperatures of 710°C and 650°C, both TS and yield strength (YS or 0.2% PS) increased with increasing reheating temperature, reaching peaks at 1 250°C, but decreased at higher temperatures. Although toughness decreased with increasing reheating temperature, it showed improvement at a reheating temperature of 1 250°C. Microstructural changes at different reheating temperatures are shown in **Photo 1** for a finishing temperature of 710°C. The microstructure mainly comprised ferrite mixed with pearlite and bainite. The α grain size was finest at a reheating temperature of 1 250°C, and coarse α grain sizes formed at a reheating temperature of 1 300°C.

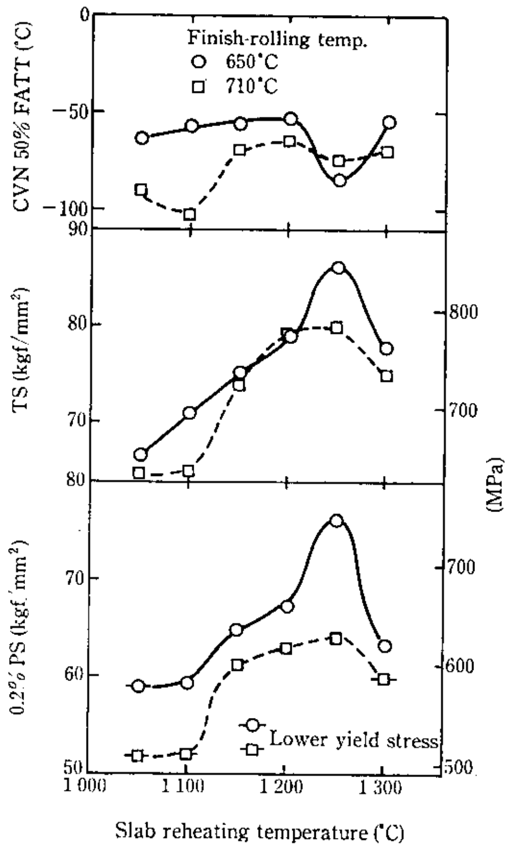
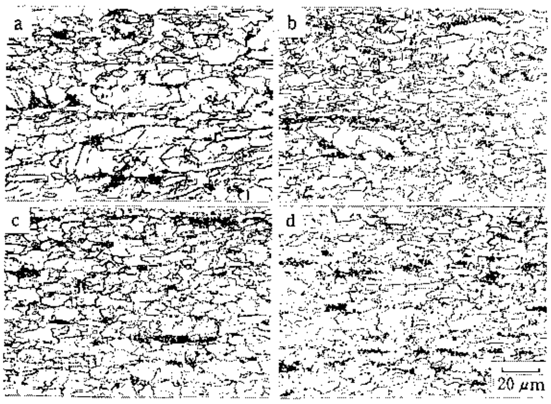


Fig. 1 Effect of slab-reheating temperature on mechanical properties

The following three phenomena are considered to be possible effects of Ti on the metallurgy of this steel grade:

(a) TiN is formed and the γ grain coarsening during slab reheating and welding is prevented.

(b) Ti is present in γ as Ti in solid solution or the



Slab reheating temperature
a: 1 300°C b: 1 250°C
c: 1 150°C d: 1 050°C

Photo 1 Microstructure change due to slab reheating temperature (finish-rolling temperature: 710°C)

strain-induced precipitation of TiC occurs, with the result that the recrystallization of γ is retarded.[8]

(c) Ti precipitates as TiC in α, contributing to precipitation hardening.

The temperature at which the whole quantity of TiC (excluding the TiN portion) dissolves is calculated for steel 1 using the solubility product of TiC in γ[9] given by Eq. (1).

$$\log [\mathrm{Ti}][\mathrm{C}] = -\frac{7000}{T} + 2.75 \cdots\cdots\cdots\cdots\cdots (1)$$

A temperature of 1 218°C is obtained. It is important to cause the dissolution of TiC during slab reheating in order to ensure that effects (b) and (c) above are fully realized. Dissolution produces effect (b), ample rolling reduction in the γ non-recrystallized region is possible, and α-nucleation sites increase. As a result, the final α structure is fine-grained. Further, precipitation hardening (c) is also enhanced.

It has been observed[10] that slightly soluble TiN begins to dissolve when reheating temperatures exceeding 1 250°C are held for more than 1 h. Further, Takahashi et al.[2] showed that the γ grain size at a reheating temperature of 1 350°C is about 3.4 times as large as that at 1 250°C in Ti bearing steel. It can be said from these results that the decrease in strength and toughness at a reheating temperature of 1 300°C observed in this study was due to the coarsening of the final α structure attributable to the γ grain coarsening promoted by the dissolution of TiN during slab reheating.

2.3.2 Relationship between rolling conditions and mechanical properties

The effect of finish-rolling temperature on strength and toughness is shown in **Fig. 2**. In the non-Ti bearing steel (steel 2 in Table 1), TS and YS increased linearly with decreasing finishing temperature, and toughness also decreased almost linearly. On the other hand, in the Ti-bearing steel reheated at 1 250°C, in which TiC dissolved completely, a strength peak was reached at a finishing temperature of 650°C and toughness did not deteriorate. In the steel reheated at 1 150°C, in which a portion of the TiC dissolved, a strength peak was also reached at a finishing temperature of about 650°C, although the peak was not as high as in the steel reheated to 1 250°C.

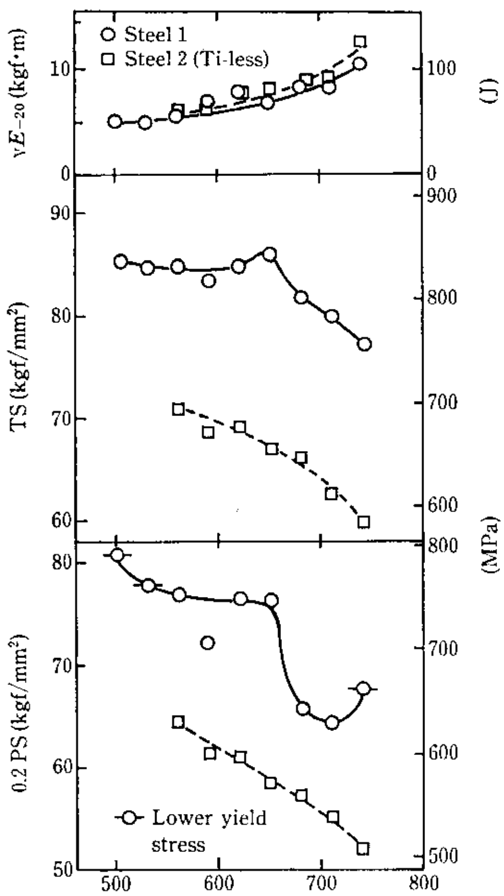


Fig. 2 Effect of finish-rolling temperature on mechanical properties

Results of an investigation into hardness changes of steel 1 when reheated from 900°C, to 1 300°C, water cooled, and then tempered are shown in **Fig. 3**. The peak of secondary hardening due to TiC precipitation occurred at a temperature near 580°C. The peak was expected to shift toward the high-temperature side due to the strain-induced precipitation caused by rolling in the α region. The strength peak of the Ti-bearing steel shown in Fig. 2 at 650°C is attributable to the strain-induced precipitation of TiC in the α phase due to the

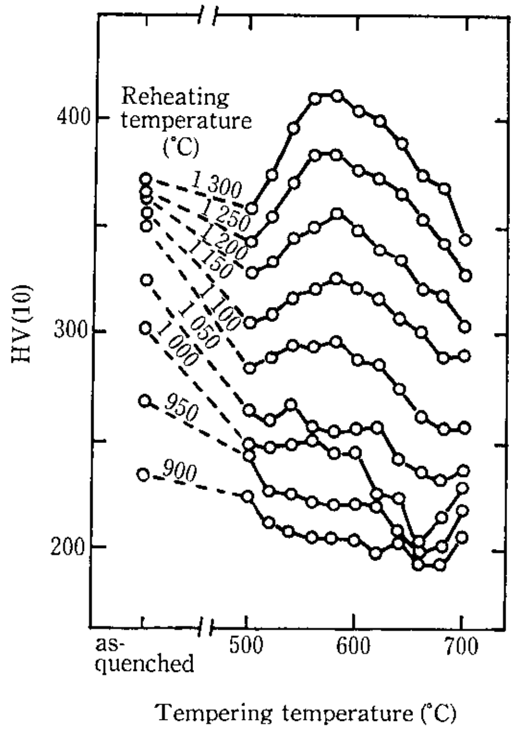


Fig. 3 Precipitation behavior of TiC

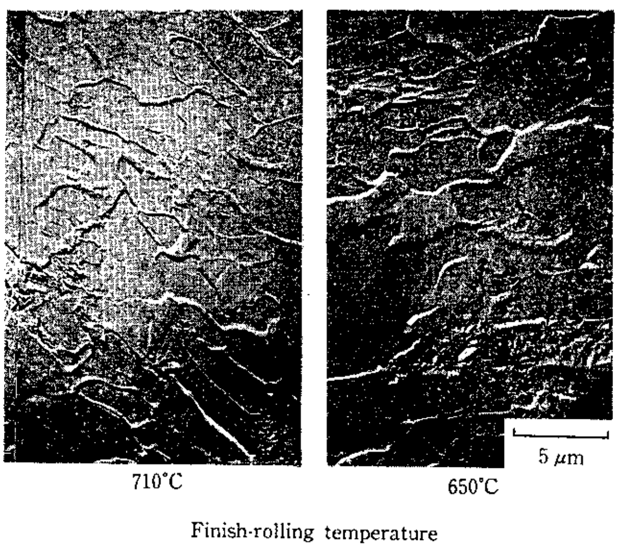


Photo 2 Substructures of deformed ferrite

($\alpha + \gamma$) dual-phase region rolling.

Results of electron microscope observation using the two-stage replica method are shown in **Photo 2**. In the Ti-bearing steel finished at 710°C, α grains formed subgrains, while a cell structure of dislocation which did not develop subgrains was observed in the steel finished at 650°C, the temperature corresponding to the strength peak. Therefore, besides precipitation hardening, the effect of retarded recovery of the deformed α also contributed to the increase in strength due to the above-mentioned strain-induced precipitation of TiC.

3 Properties of Developed Steels

Steel compositions were examined in addition to the basic laboratory examination of the process factors described in Sec. 2. On the basis of these results, as-plate-rolled HT 70 steel plates with a thickness of 25.4 mm and as-plate-rolled HT 80 steel plates with a thickness of 12.7 mm were manufactured on a commercial scale using a plate mill. Target properties of the two types of steel plates are given in **Table 2**. This section describes the properties of these newly-developed steels.

Table 2 Aimed properties of steel plates

Steel	Thick. (mm)	Tensile properties (T-direction)		Bending property*1	Impact properties*2 (L-direction)	
		YS (kgf/mm²) (MPa)	TS (kgf/mm²) (MPa)	Test condition	Test temp. (°C)	Av. absorbed energy (kgf·m) (J)
HT70	25.4	60≤ (588≤)	70~85 (686~833)	180° bending	−15	4.0≤ (39≤)
HT80	12.7	70≤ (686≤)	80~95 (785~932)	Radius: 1.5t	−15	3.6≤ (35≤)

*1 Test piece JIS Z 2204 No. 1
*2 Test piece JIS Z 2202 No. 4 (V-notch)

3.1 Basic Properties of Steels

The chemical compositions of the newly-developed steels are given in **Table 3**. As the strength of steel plates can be controlled by controlled-rolling appropriate to the plate thickness, the two steels have almost the same chemical composition; the C_{eq} and P_{cm} were very low, in spite of the high tensile strength values.

Table 3 Chemical compositions newly-developed steel plates (wt. %)

Steel	Thick.	C	Si	Mn	P	S	Nb	Ti	C_{eq}	P_{cm}
HT70	25.4 mm	0.09	0.53	1.87	0.019	0.004	0.040	0.18	0.40	0.201
HT80	12.7 mm	0.10	0.52	1.81	0.019	0.003	0.039	0.18	0.40	0.208

Table 4 Tensile and bend test results of steel plates

Steel	Thick. (mm)	Test Direction	Tensile Test*1 YS (kgf/mm²) (MPa)	Tensile Test*1 TS (kgf/mm²) (MPa)	Tensile Test*1 El (%)	Bend Test 180° bending $R=1.5t$
HT70	25.4	L	64 (628)	73 (716)	27	Good
		T	67 (657)	77 (755)	26	Good
HT80	12.7	L	73 (716)	82 (804)	30	Good
		T	76 (745)	85 (834)	27	Good

*1 Test piece: JIS No. 4 for thickness 25.4 mm
JIS No. 5 for thickness 12.7 mm

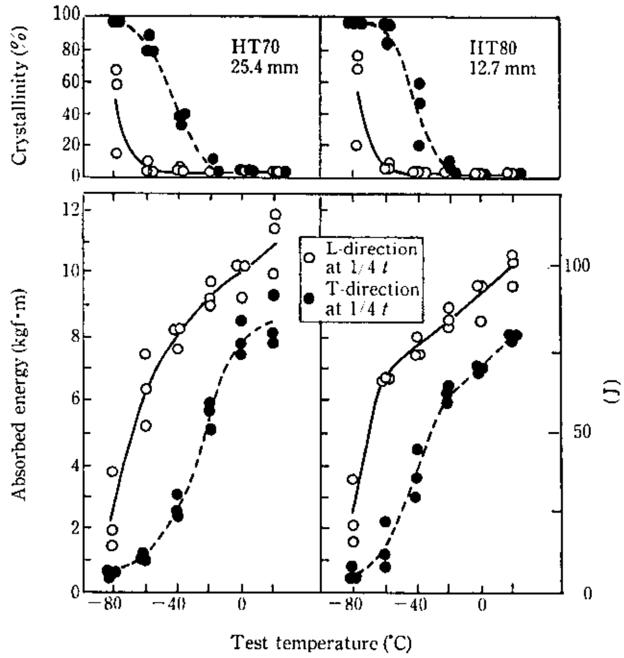


Fig. 4 V-notch Charpy transition curves

Results of the tensile test and bending test are listed in **Table** 4, and Charpy transition temperature curves are shown in **Fig.** 4. Differences in mechanical properties were observed between the longitudinal and transverse test directions because controlled-rolling including the rolling in the ($\alpha + \gamma$) dual-phase region was conducted. Despite the differences, there was no problem with the values of the mechanical properties themselves.

3.2 Formability

Cold formability, especially formability in bending, is required for construction equipment applications. The wide plate bending test was conducted by varying the condition of the prepared edges. The test method employed is shown in **Table 5**. Results of the test of the HT 70 and HT 80 steel are shown in **Figs. 5** and **6**, respectively. The as-flame-cut edges showed excellent cold bending formability, as shown in Fig. 5. The hardness test by flame cutting showed that the thickness of

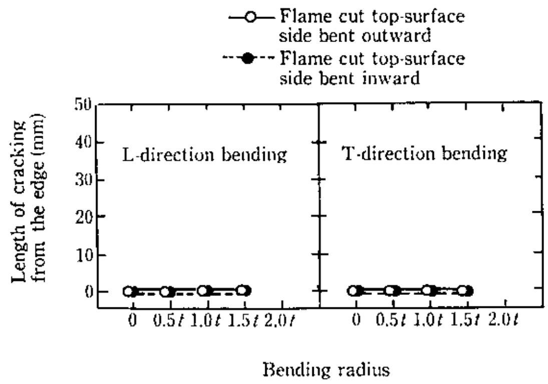
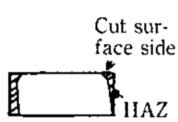
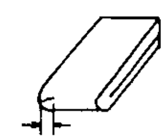
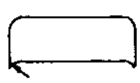


Fig. 5 Wide-width bend test results of as-flame-cut sample (HT70, 25.4 mm)

Table 5 Test conditions for cold bending

Steel	Specimen Size (mm)	Specimen Direction	Specimen Edge preparation	Bending Method	Bending Angle	Bending Direction	Evaluation Crack length
HT70	25.4 t × 150 W × 350 L	L, T	As flame cut 	Roller bending	180°	Inward and outward bending of the cut top-surface side	 Length of cracking from edge
HT80	12.7 t × 150 W × 350 L	L, T	As shear cut 	Roller bending	180°	Inward and outward bending of shear cut burr	

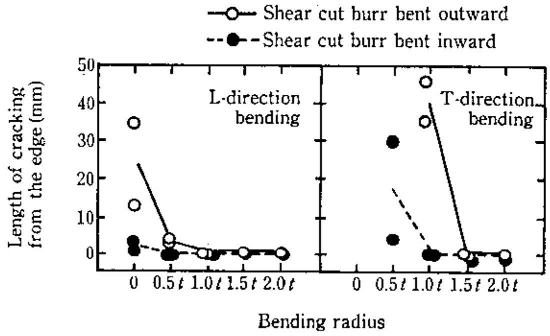


Fig. 6 Wide-width bend test results of as-shear-cut sample (HT80, 12.7 mm)

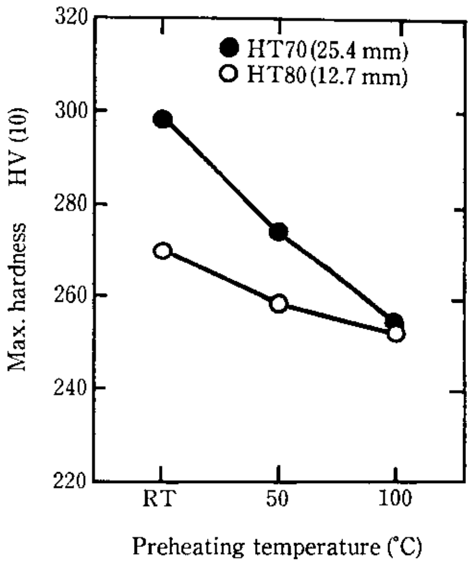


Fig. 7 Result of maximum hardness test

the hardened layer was about 1 mm and the hardness of this layer was HV 300 or less. This low hardness was due to the low C_{eq}.

In the as-sheared condition, the bending radius is limited to 2.5 to 3.5 t[7] in conventional as-hot-rolled HT 80 steel sheet, while bending radii of 2.0 t minimum are possible with the newly-developed HT 80 steel plate, as shown in Fig. 6. Severer forming is possible and bending radii of 0.5 t minimum are possible if special attention is paid to bending conditions, for example, if the bending direction is the same as the rolling direction or if the shearing burrs are on the inside of the bend.

3.3 Weldability

The maximum hardness test specified in JIS Z3101 was conducted under the welding conditions given in **Table 6**. Results are shown in **Fig. 7**. Even at a plate thickness of 25.4 mm, the hardness was HV 300 or less without preheating. From the relationship between C_{eq} and HV_{max}, the hardenability of the new steels was judged to be equivalent to that of conventional HT 60 steel plate.

Table 6 Welding conditions for maximum hardness test

Specimen thick.	20 mm*(HT70) 12.7 mm (HT80)
Welding rod	KSA 106, 4 mmφ
Current	170 A
Voltage	25 V
Speed	2.5 mm/s

* Thickness was reduced to 20 mm from 25.4 mm according to JIS provisions

The Y-groove weld cracking test specified in JIS Z3158 was conducted on 25.4 mm thick HT 70 steel plates under the welding conditions shown in **Table 7**. Results are shown in **Fig. 8**. For gas metal arc welding (GMAW), the temperature for preventing weld cracking was 0° or under. This temperature was 50°C even with shielded metal arc welding (SMAW). Therefore, fabrication without preheating is possible at room temperature when restraints are not very severe, as is the case with construction equipment.

3.4 Properties of Welded Joints

SMAW and GMAW joints were prepared using 25.4-mm thick HT 70 steel plates under the welding conditions given in **Table 8** (GMAW joints are frequently used in construction equipment). The tensile and bending properties of the welded joints are shown in **Table 9**. In both short-gauge and long-gauge specimens, the TS

Table 7 Welding conditions for Y-groove weld cracking tests of HT70

Method	Welding						Plate	Thickness
	Conditions				Atmosphere			
	Wire	Current	Voltage	Speed	Air temp.	Humidity		
GMAW	KM 60, 1.6 mmφ	300 A	31 V	4.5 mm/s	15°C	60%	HT70	25.4 mm
SMAW	KSA 106, 4 mmφ	170 A	23 V	2.5 mm/s	11°C	53%		

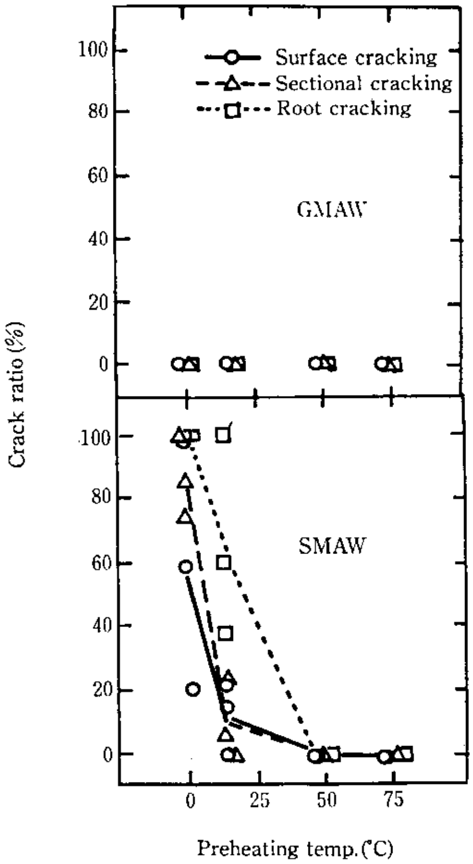
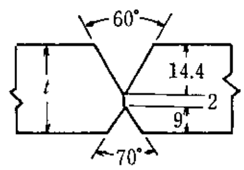


Fig. 8 Result of Y-groove weld cracking test of HT70

Table 8 Welding conditions for HT70

	SMAW	GMAW
Welding wire	KSA106 4 mmϕ	KM60 1.6 mmϕ
Shielding gas	—	Ar80% + CO_2 20%
Preheating temperature	Room temp.	Room temp.
Interpass temperature (°C)	70～110	70～120
Current (A)	170	310
Voltage (V)	25	33
Speed (mm/s)	2.5	5.2
Heat input (kJ/mm)	1.7	2.0
Groove shape	(mm) 	

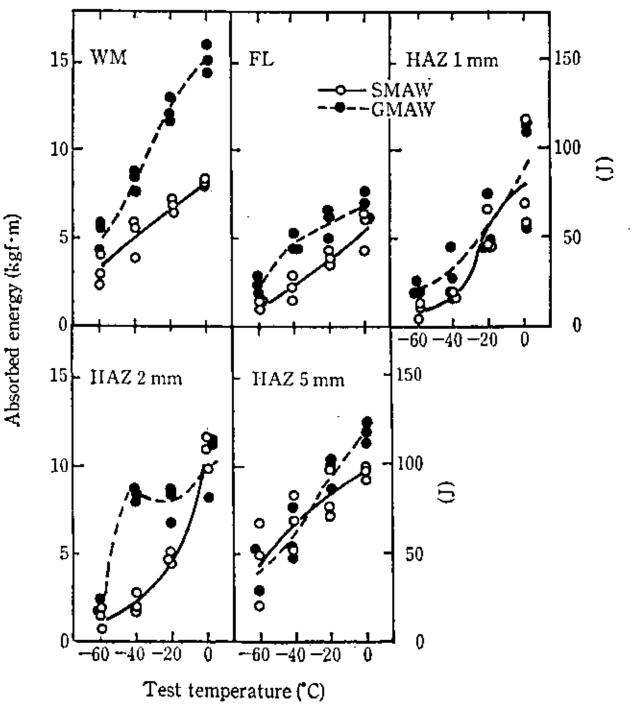


Fig. 9 Charpy impact transition curves of welded joints

Table 9 Mechanical properties of welded joints

Welding method	Tensile test (L direction)				Bend test
	Test piece	YP (kgf/mm²) (MPa)	TS (kgf/mm²) (MPa)	Position of fracture*1	Side bend $R=1.0t$
SMAW	Shorter gauge	—	74.4 (730)	WM	Good
		—	73.6 (722)	BM	
	Longer gauge	62.8 (615)	72.2 (708)	BM	Good
		61.0 (598)	71.5 (701)	BM	
GMAW	Shorter gauge	—	74.0 (726)	BM	Good
		—	73.7 (723)	BM	
	Longer gauge	60.7 (595)	72.3 (709)	BM	Good
		61.5 (603)	73.4 (720)	BM	

*1 WM: Weld metal
BM : Base metal

of the joints was equivalent to that of the base metals.

Results of the Charpy impact test are shown in **Fig. 9** for each notch position. Even at the fusion line (FL), which showed the greatest deterioration, the absorbed energy was not less than 3 kgf·m (29 J) at a test temperature of −20°C.

3.5 Fatigue Properties

The tensile-type fatigue test was conducted using 25.4-mm thick HT 70 steel plates in accordance with JIS Z3103. Two types of surface finish were used in the specimens, one with both surfaces polished, and the other with mill scale left on one side; the specimen thickness was 12.5 mm. Results of the test are shown in **Fig. 10**. Even the fatigue limit of the specimen with mill scale on one surface was slightly higher than 50% of its tensile stress, showing the same behavior as that of conventional HT 80 steel.

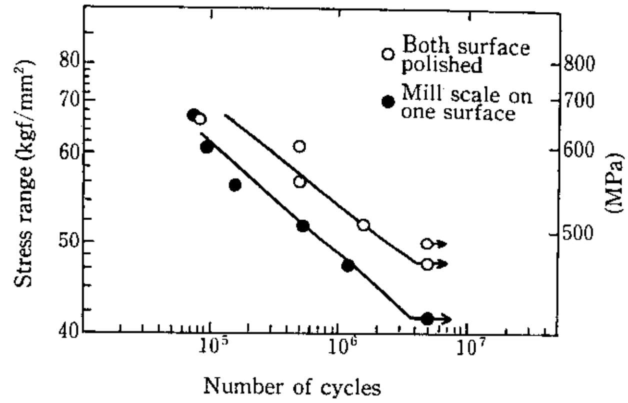


Fig. 10 Result of tensile-type fatigue test

4 Conclusions

Laboratory experiments and manufacturing with a plate mill were carried out to develop heavy-gauge non-quench-tempered HT 70 and HT 80 steel plates for construction equipment, with the aim of fabrication in the as-plate-rolled condition. The following results were obtained:

(1) The optimization of rolling in the $(\alpha + \gamma)$ dual-phase region produces a combined effect of strain-induced precipitation of TiC and suppression of recovery of deformed α, enhancing strength with no deterioration in toughness.

(2) To obtain the above-mentioned effect, TiC must be dissolved during slab reheating without dissolving TiN.

(3) In spite of their low C_{eq}, 12.7-mm thick HT 80 steel plates and 25.4-mm thick HT 70 plates manufactured on a commercial scale using the above-mentioned process conditions showed good base-metal properties.

(4) The cold bending formability of the newly-developed steels was superior to that of the conventional as-hot-rolled HT 80 steel. Tight bending was possible with flame-cut edges. In the as-sheared condition, bending with a bending radius of 0.5 t minimum is possible if special attention is paid to the bending direction and the side of burr formation.

(5) The maximum hardness in the heat-affected zone of the newly-developed steels was approximately equal to that of the conventional HT 60 steel.

(6) Results of the Y-groove weld cracking test showed that fabrication without preheating is possible at room temperature.

(7) The toughness of welded joints showed good levels for applications such as construction equipment.

(8) The fatigue limit of a specimen with mill scale on one surface was slightly higher than 50% of its tensile strength, showing the same behavior as that of the conventional HT 80 steel.

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