KAWASAKI STEEL TECHNICAL REPORT
No.42 (May 2000)

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Tatsumi Kimura, Takanori Okui, Kiyoshi Uchida

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The new TMCP (thermo-mechanical control process) method is a process to enhance ferrite nucleation by using VN precipitates to refine the microstructure, and it is an integrated control method of microstructures applicable to the rolling of the heavy gauge H-shapes, to which the restrictive conditions of rolling, including the cooling process should be ensured. As a result of applying the new TMCP method to 355 MPa class heavy gauge H-shape with dimensions of 612 × 500 × 50 × 80 mm, its microstructure was remarkably refined, giving high strength and excellent toughness. The full-scale loading tests, carried out on a column-beam structure, in which a column consisted of this newly developed heavy gauge H-shape, proved that the column has sufficient deformation capacity and was verified as a safe material for high-rise buildings. The heavy gauge H-shapes, under the bland names of RIVER TOUGH 325 and 355, which satisfy SN490CTMC and SM520CTMC of the JIS grades, have been in production with flange thickness up to 80 mm.

1 Introduction

Because heavy gauge H-shapes have a large cross section comparable to thick plate box columns assembled by welding, their application as a column material for high-rise building structure is increasing now. The heavy gauge H-shapes have the merits such as improving the safety of building structures, shortening the delivery due date etc. due to decreasing of the areas to be welded.

Refinement of the microstructure has been insufficient because multi-stage rolling with light reduction under high temperature heating is unavoidable in the H-shape rolling due to the restrictions from mill capacity and profile control, and it has been difficult to obtain the performance equivalent to the TMCP (thermo-mechanical control process) thick plate produced with a plate mill[1].

In order to overcome such weak points of heavy gauge H-shapes and to offer a column material comparable to box columns made of thick plate, it was necessary to develop a new TMCP method suitable to the manufacturing process of H-shapes. That is refinement of the microstructure needs to be enhanced by other methods in lieu of conventional TMCP by the improvement of the transformation driving force as being less dependent on rolling strain and/or cooling.

In this report, the metallurgical features of the new TMCP, to which the fine inclusion metallurgy (FIM) was introduced for utilizing fine inclusions as ferrite nucleation sites is described and the performance of the base metal, susceptibility to cold cracking, and the welded joint characteristics of the SM520MPa grade heavy gauge H-shape produced using this new TMCP are shown compared with the conventional TMCP heavy gauge H-shape.

2 Development of a New TMCP Applicable to the Manufacturing Process of Heavy Gauge H-Shapes

2.1 Hot Rolling of Heavy Gauge H-Shapes

Table 1 shows the differences of the hot rolling conditions between heavy gauge H-shapes and TMCP thick plate. Heavy gauge H-shapes require reheating to the temperature higher than TMCP thick plate for rolling. And, therefore, the initial austenite grain size is relatively coarse. The reduction in recrystallization region is

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* Originally published in *Kawasaki Steel Giho*, **30**(1998)4, 215–221

Table 1 Hot rolling conditions of heavy gauge H-shape and thick plate

Item	Heavy gauge H-shape	Thick plate
Reheating temperature (°C)	≧1 150	*ca.* 1 150
Total reduction (%)	≦50	75
Reduction par pass in the recrystallization region (%)	5~10	10~15
Reduction in the non-recrystallization region (%)	0	*ca.* 30
Cooling condition	AC	ACC

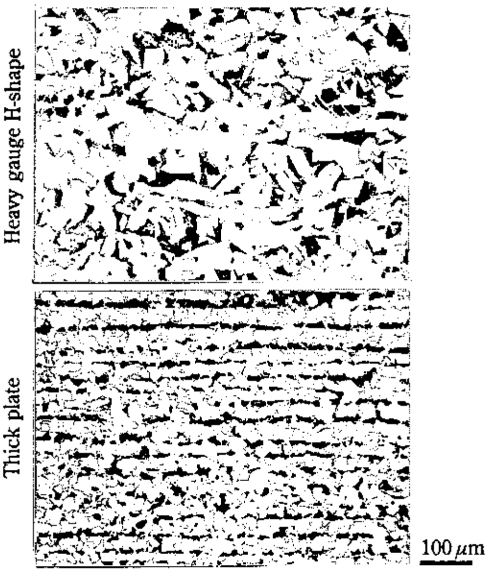


Photo 1 Microstructures of heavy gauge H-shape and thick plate

also so small that sufficient refinement of austenite grain is hardly processed. Furthermore, at the cooling stage after hot rolling, air cooling is preferred in order to make precise shape control by uniform cooling covering the whole cross section.

Photo 1 shows the comparative microstructures of heavy gauge H-shapes and TMCP thick plates. According to the difference in the hot rolling and cooling methods mentioned above, refining of the microstructure for heavy gauge H-shapes is insufficient compared to TMCP thick plate, and this makes it considerably difficult to obtain high strength and high toughness. Therefore, microstructure refinement of heavy gauge H-shapes needs a new TMCP in lieu of the existing TMCP, which is much dependent upon the hot rolling and cooling conditions.

2.2 Ferrite Nucleation Potency of Various Inclusions

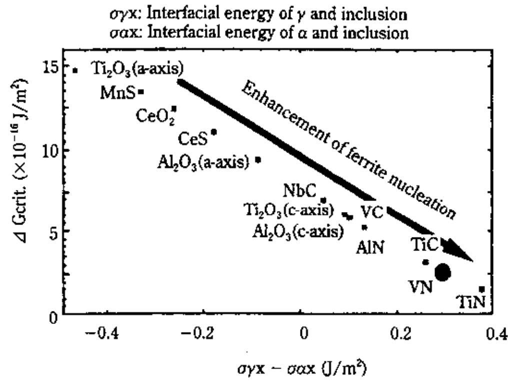


Fig. 1 Change in interfacial energy and driving force for nucleation of ferrite at various inclusions

FIM, by which fine precipitates and/or inclusions dispersed in steel are utilized as ferrite nucleation sites, has been noticed recently[2–7]. The interfacial energy, which is determined by the lattice coherency as the interface of fine inclusions and ferrite, is an important factor for ferrite nucleation potency[8]. **Figure 1** shows the change of the interfacial energy and driving force for ferrite nucleation caused by various fine inclusions. Vanadium nitride (VN) has a high ferrite nucleation potency compared to titanium nitride (TiN). Furthermore, VN has been selected for heavy gauge H-shapes regarding the refinement of microstructures together with precipitation strengthening.

2.3 Refining Behavior of Microstructure of VN-Steel by VN Precipitates

Photo 2 shows some electron-microscopic photographs of the microstructure of VN-steel with a suitable V and N amounts, at the midway of the ferrite transformation. They show the ferrite transformation easily occurs from VN particle which has been precipitated in the austenite phase. **Photo 3** compares the ferrite transformation behavior between the VN-steel and a conventional steel. As for VN-steel, not only did the number density of the intra-granular ferrite grains increase, but the number density of the grain boundary ferrite increased during the ferrite transformation.

To confirm the effect of the microstructure refinement when applying FIM to heavy gauge H-shapes, some laboratoric hot rolling with conditions equivalent to those in the actual production were carried out and the change of the microstructure and the mechanical properties were investigated. **Figure 2** shows the effect of the reduction in the non-recrystallization region on the number density of the ferrite grains. It indicates that the VN-steel was considerably refined the ferrite grains under the rather smaller reduction compared with the conventional Nb-steel. Due to the intensified refinement, the VN-steel exhibited great improvement in strength and toughness as the relationship between the 0.2% proof

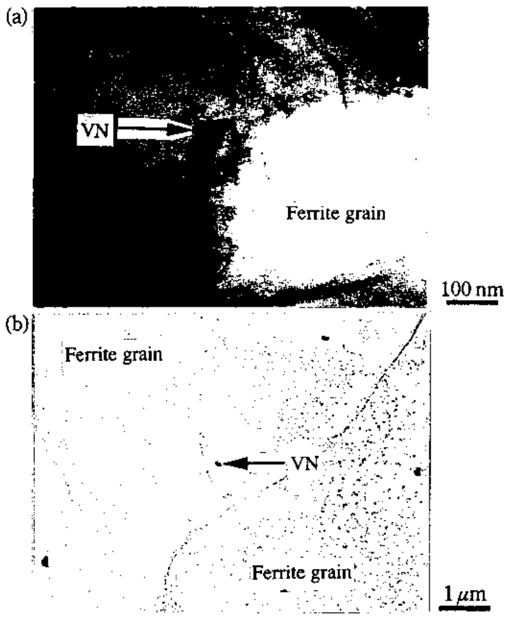
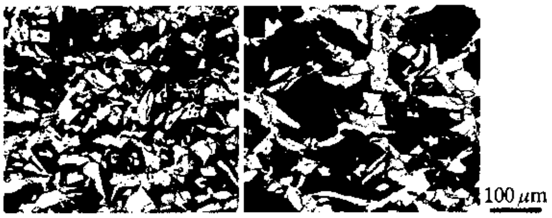


Photo 2 Electron micrographs of ferrite transformation through VN precipitates; (a) cooled at a rate of 0.1°C/s from 950°C to 630°C and then quenched at 630°C to a room temperature (thin film), (b) cooled at a rate of 0.1°C/s from 950°C to a room temperature (carbon extration replica)



V and N bearing steel Conventional steel

Photo 3 Microstructure change of V and N bearing steel compared with conventional steel; cooled at a rate of 0.1°C/s from 950°C to 630°C and then quenched at 630°C to a room temperature

strength and the Charpy absorbed energy at 0°C is shown in **Fig. 3**.

2.4 Concept of the New TMCP and Its Characteristics

Figure 4 illustrates the concept of the new TMCP. On the basis of the optimized addition of V and N in combination, this process needs two metallugical stages in hot rolling. The first stage is the rolling in the partial recrystallization region for repeated refinement of the austenite grains. The second one is introducing strain to promote the precipitation of VN in the interior of the austenite as well as at the grain boundary of the austenite. This two stage rolling activates the ferrite transformation not only from the austenite grain boundary but in the grain interior by seeding many ferrite nucleation sites of the VN precipitates in the followed cooling. The new TMCP should be a method most fit to the rolling of heavy gauge H-shapes because it makes a great effect on the microstructure refinement in a relatively high temperature rolling as well as for smaller reduction.

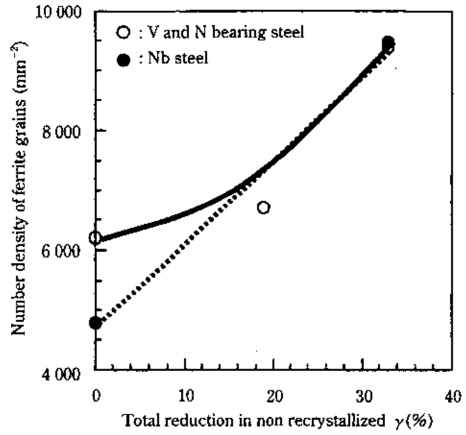


Fig. 2 Relation between the reduction in the non-recrystallization region and the number density of ferrite grains

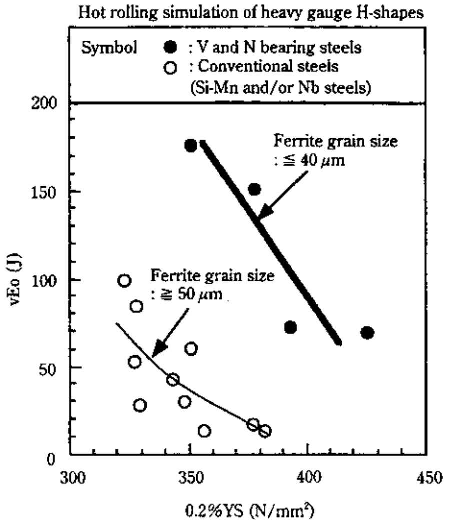


Fig. 3 Improvement of strength and toughness for V and N bearing steels

3 Performance of Heavy Gauge H-Shapes Produced by the New TMCP

3.1 Manufacturing Practice

An SM520CTMC grade heavy gauge H-shape was manufactured by the new TMCP. **Figure 5** shows a typical manufacturing process diagram. A beam blank was

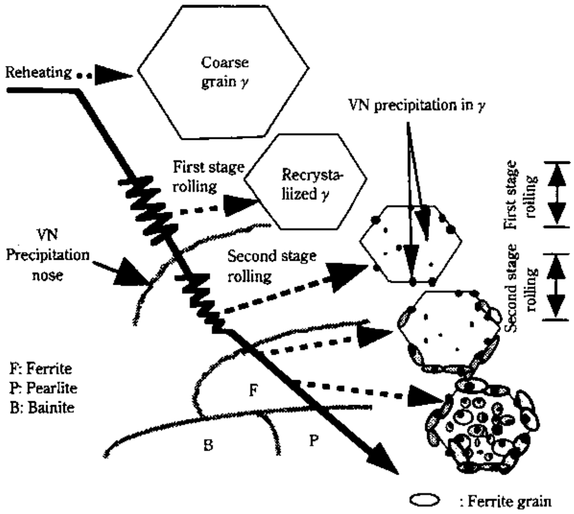


Fig. 4 Microstructure control of the new TMCP for heavy gauge H-shape

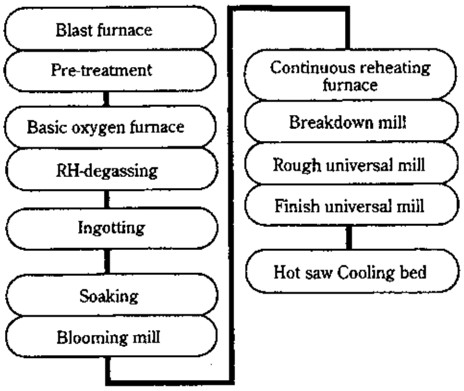


Fig. 5 Manufacturing process of heavy gauge H-shape

prepared to the new TMCP by blooming an ingot of the VN-steel. Following the reheating, it was rolled to a heavy gauge H-shape sized to 612 × 500 × 50 × 80 mm by the universal mill. The reheating temperature and the temperature during rolling were controlled strictly. **Table 2** shows a typical chemical composition of the developed steel. Suitable amounts of Cu and Ni were microalloyed with the optimum V-N combination to 0.12%C-1.35%Mn-0.065%V steel, but the carbon equivalent was kept law at 0.39%.

Table 2 Typical chemical compositions of the new TMCP type heavy gauge H-shape and conventional one
(mass%)

Steel	C	Si	Mn	Al	V	Others	Ceq	Pcm
Developed	0.13	0.38	1.38	0.028	0.066	Cu, Ni, N	0.39	0.25
Conventional	0.15	0.38	1.50	0.030	0.060	Cu, Ni	0.43	0.27

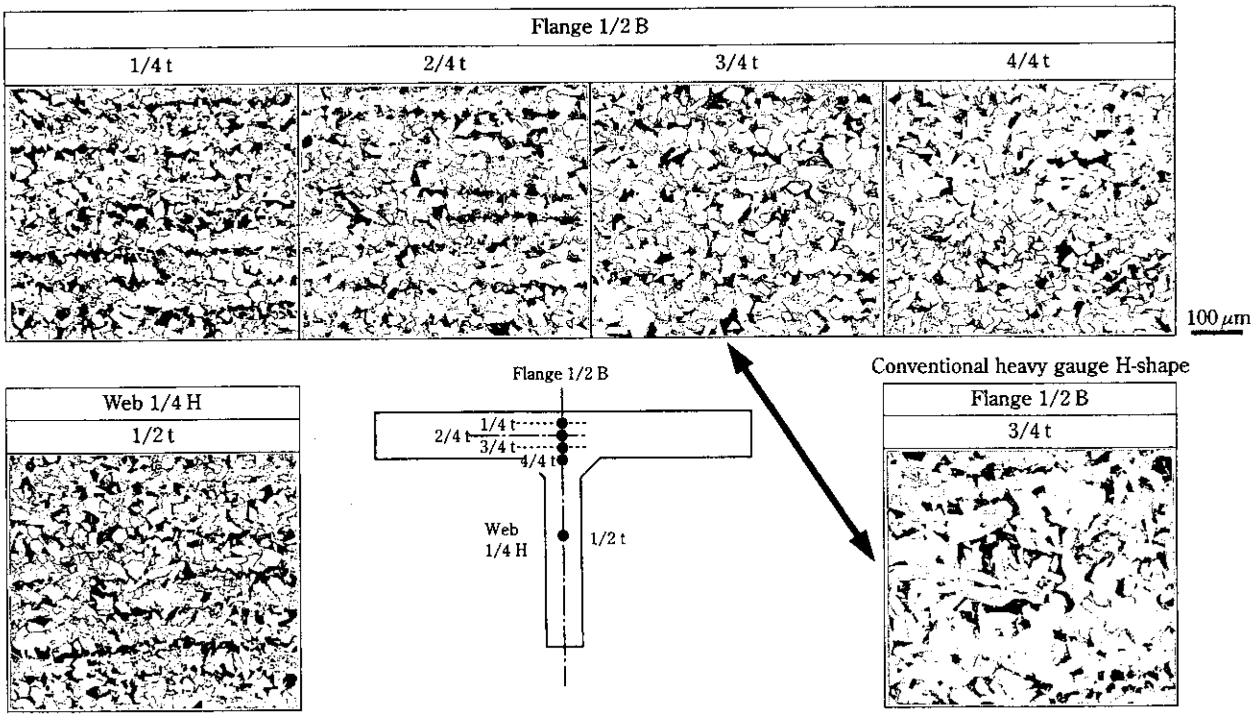


Photo 4 Microstructures of the new TMCP type heavy gauge H-shape at specific protions

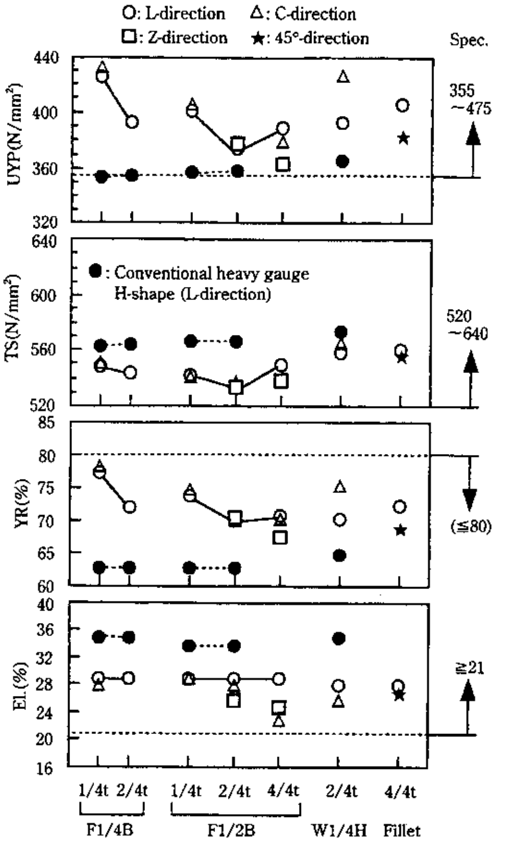


Fig. 6 Mechanical properties of the new TMCP type heavy gauge H-shape at specific portions compared with conventional one

3.2 Performance of the Base Metal of the Developed Heavy Gauge H-Shape

Photo 4 shows the change of the microstructure in the flange thickness direction at the F1/2B portion of the developed heavy gauge H-shape. An example of a conventional heavy gauge H-shape with a carbon equivalent of 0.43% is also shown in the photograph for comparison. It is clear that the microstructure of the developed product is remarkably more refined. Furthermore, the change of the microstructure in the flange thickness direction is minimal and a fine ferrite-pearlite structure is observed at the difficult 4/4 t area in the vicinity of the fillet area.

Figure 6 shows the tensile properties at various specific locations. It is clear that the developed heavy gauge H-shape has yield strength higher than the targeted 355 MPa throughout the cross section. A low yield ratio such as below 80% is achieved and an elongation more than 21% can also be attained. The Charpy impact test in the L-, C- and Z directions at the various specific locations proved the toughness as shown in **Fig. 7**. The fracture appearance transition temperature of the developed heavy gauge H-shape was lowered by about 40°C from that of the conventional steel. It is noted that the absorbed energy in Z-direction is higher than 50J at 0°C, which is typical to the TMCP plates with equivalent thickness. **Figure 8** shows hardness distribution in the section at various locations. The hardness difference between the center and the surface layer is as small as HV25, and the change in average hardness with location is hardly recognized.

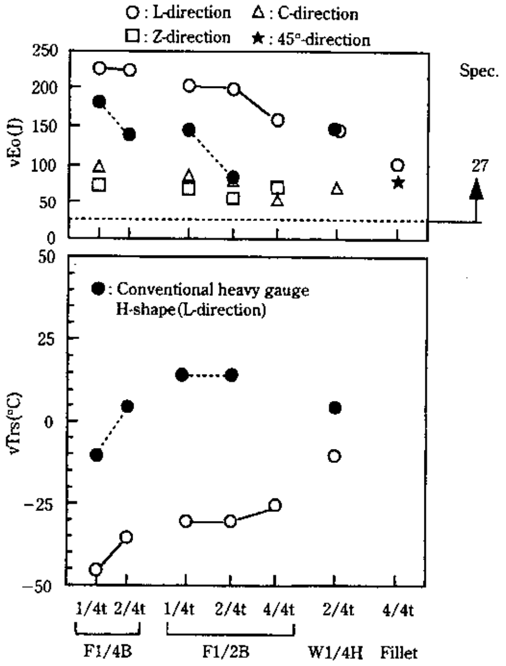


Fig. 7 Charpy impact test results of the new TMCP type heavy gauge H-shape at specific portions compared with conventional one

3.3 Susceptibility to Cold Cracking

A maximum hardness test and the y-groove weld cracking test by using the JIS Z 3101 method and the JIS Z 3158 method were conducted to evaluate susceptibility to cold cracking. The results of these tests are summarized in **Figs. 9** and **10**, respectively. The maximum hardness in the heat-affected zone (HAZ) was as low as HV280, which is much lower than those of the conventional heavy gauge H-shape. No weld cracking occurred even under the non-preheating condition in the y-groove weld cracking test.

3.4 Mechanical Properties of Welded Joint

To investigate the performance of the column-beam and column-column welded joints, the joints were welded by multi-layered CO_2 arc welding, which is a usual welding method in the actual construction. **Table 3** shows the welding conditions. An SN490A grade plate with thickness of 40 mm was used as the material for the beam flange. The tensile test specimens for the welded joints with the whole thickness and Charpy impact spec-

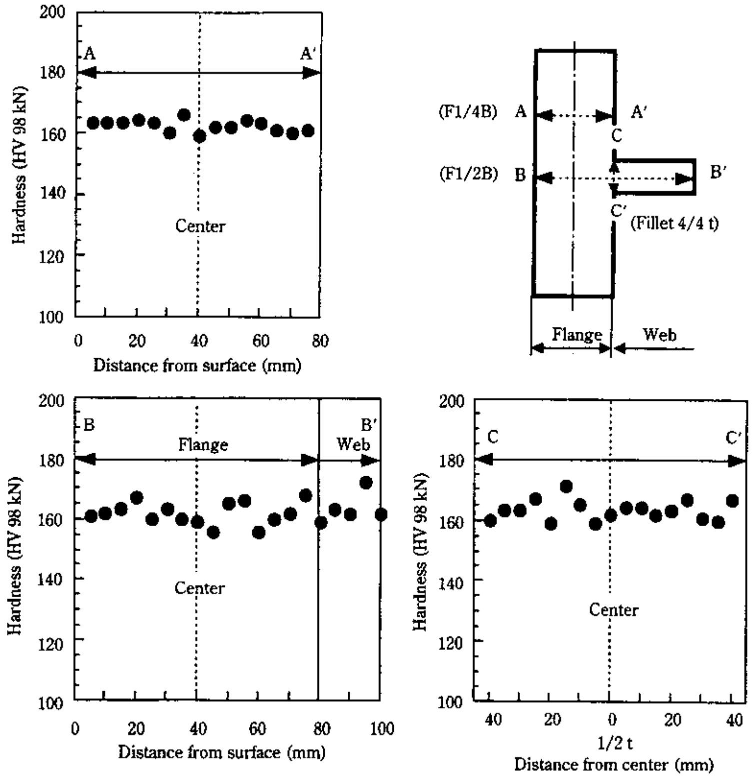


Fig. 8 Hardness distributions for the new TMCP type heavy gauge H-shape

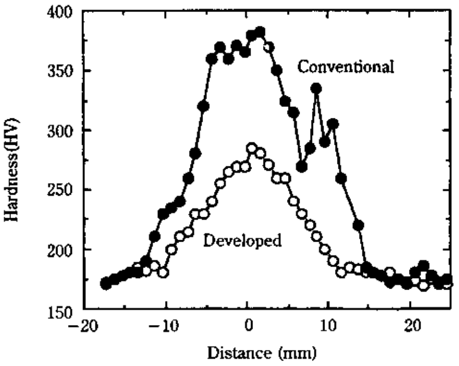


Fig. 9 Maximum hardness test results of the new TMCP type heavy gauge H-shape

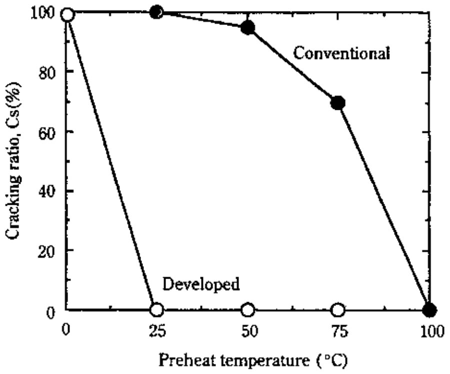


Fig. 10 Results of y-groove weld cracking test for the new TMCP type heavy gauge H-shape

Table 3 Welding conditions of various welding

Welding joint	Position	Pass	Current (A)	Voltage (V)	Travel speed (cm/min)	Heat input (kJ/cm)
Column to beam	Horizontal-fillet (uphill)	16~24	290~330	37	31~56	12~23
Column to column	Horizontal-uphill	61~68	270~300	34~35	32~59	10~19

Welding method: CO_2 gas welding, Preheat temp.: ≧ 100°C, Inter-pass temp.: 105~205°C, Welding electrode: KC-50

imens were carried out to evaluate the joint performance. **Table 4** shows the tensile properties of the welded joints. The portions of rupture were in the base metal of the beam or the heavy gauge H-shape flange, and no rupture from HAZ has been observed. **Figure 11** shows the results of the impact tests for the welded joint. The Z-direction tests were executed for the column-beam joint and in the L-direction for the column-column joint. Regarding the HAZ and the weld metal of the column-beam joint, a slight degrease in the impact perfor-

Table 4 Tensile test results of flange and beam welded joints

Sample	T.S. (N/mm^2)	Fracture position
Convex test piece	592 592	Plate Plate
No convexity	540 553	H-shape H-shape

Sample (direction)	Position	Absorbed energy. vEo (J)		
		HAZ*	Bond	WM
Column to beam (Z)	Ⓐ	89 (45)	84 (43)	123 (28)
Column to column (L)	Ⓑ	224 (13)	220 (5)	134 (15)

*HAZ: 1 mm from F.L. ( ): B.A. (%)

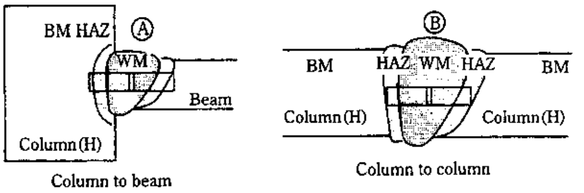


Fig. 11 Charpy impact test results of welded joints

mance was observed compared with the column-column joint, while the absorbed energies at 0°C were still kept high level such 89J and 84J, respectively, cleavage area was smaller than 50% and good welded joint toughness were verified.

3.5 Structure Performance of Welded Column-Beam Component

To confirm the safety of the new TMCP heavy gauge H-shapes when it is used as a material for columns of high-rise buildings, a full-scale structure with the same weld access hole as the work on site would be, was built for loading test. Regarding the test article of which the ratio of the yield strength of the beam to the yield strength of the column is set to about 0.6, the obtained results included a maximum yield strength (Qmax): 1 799 to 1 836 kN, ratio of maximum yield to panel yield strength (Qmax/Qpy): 1.45 to 1.48, cumulative plastic deformation magnification (η_f): 19.9 to 27.7, which means the structure exhibits sufficient yield strength and plastic deformation ability[9]. The full-scale loading test was ended due to the buckling of a beam, and no damage such as cracks or local buckling were recognized on the heavy gauge H-shape at all. This result shows that the developed new TMCP heavy gauge H-shapes have sufficient safety as a column material for high-rise buildings.

4 New TMCP Heavy Gauge H-Shape Products

4.1 Available Product Sizes and Grades

The new TMCP heavy gauge H-shapes utilizing FIM are on the market under the brand names of "RIVER TOUGH 325" (RT325) and "RIVER TOUGH 355" (RT355) series. These are guaranteed to have properties equivalent to or better than SN490CTMC and SM520CTMC of the JIS Standard, respectively. **Figure 12** shows their available product sizes. Their current maximum producible flange thickness is 80 mm. The projects, which are applied RIVER TOUGH to are listed in **Table 5** and **Photo 5** shows an example of the projects. RIVER TOUGH has been accumulated its application to several thousands of tons now, because its high and stable strength and toughness regardless of flange thickness have been appreciated.

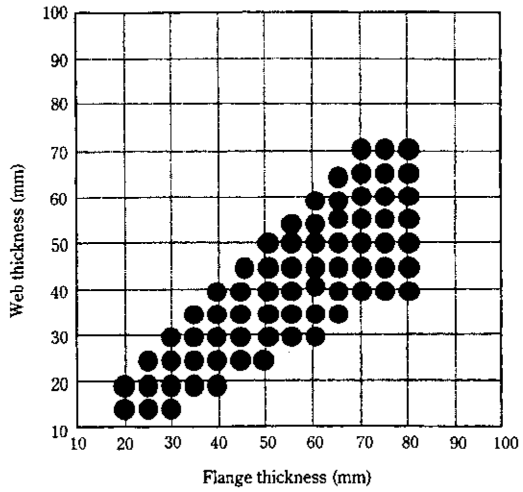


Fig. 12 Available thickness combinations of RT325 and RT355 (H500 × 500 series)

5 Conclusions

The conventional TMCP has been advanced to a new one which does not depend on rolling or cooling conditions by integrating its metallurgical advantages with a new microstructural control with fine precipitates (FIM). The metallurgical features of the new TMCP and the properties of the brand new products by it are summarized.

(1) A new TMCP applicable to heavy gauge H-shapes use finely dispersed VN precipitates, which are of highest ferrite nucleation potency, to refine the microstructure.

(2) As a result of applying the new TMCP to 355 MPa grade heavy gauge H-shape of 612 × 500 × 50 × 80 mm in size, strength and toughness were remarkably improved. In particular, the toughness in the Z-direction as well as the toughness of the F1/2 and fillet portions at the mid thickness of the flange indicated satisfactory values.

(3) It was confirmed that the developed steel had low susceptibility to cold cracking and high joint performance. Furthermore, as a result of the full-scale load-

Table 5 Application of the new TMCP type heavy gauge H-shape "RT325, RT355"

No.	Project	Designer	Scale	Details		
				Spec.	Max. thickness (mm)	Delivery
1	Doujima Avanza	Nikken Sekkei Ltd.	2B-24F 95 000 m^2	RT-325B (SN490B) TMC	75	'96.9~
2	Kobe International House	Nikken Sekkei Ltd.	3B-22F 56 540 m^2	RT-325B (SN490B) TMC	80	'97.2~
3	Meiji Seimei Aoyama	Takenaka Co.	B3-13F 41 680 m^2	RT-355B (SN520B) TMC	70	'97.2~
4	Harumi 1 Chome Urban Renewal Project (Z Build.)	Nikken Sekkei Ltd. Kume Sekkei Co. Ltd. Yamashita Sekkei Inc.	B4-33F 100 800 m^2	RT-325B	65	'97.11~
5	Harumi 1 Chome Urban Renewal Project (X Build.)	Nikken Sekkei Ltd. Kume Sekkei Co. Ltd. Yamashita Sekkei Inc. Takenaka Co.	B4-44F 130 000 m^2	RT325C (SN490C) TMC	70	'98.2~

Photo 5 Kobe International House

ing test, it was also confirmed that a column made of the developed steel gives satisfactory safety to high-rise buildings.

(4) The brand new heavy gauge H-shapes, RT325 and RT355 by the new TMCP, which satisfy the SN490CTMC and SM520CTMC of JIS Standard is being manufactured with the current maximum flange thickness of 80 mm. They need no decrease of the design standard strength (F value) with thickening of flange thickness. Up to now, these new heavy gauge H-shapes have been applied to five projects on several thousands of ton scale and highly appreciated by the customers.

Further development of the new TMCP heavy gauge H-shapes to higher strength, better quality, and widening of their size availability has been now going so as to satisfy the upcoming customer's requests.

6 Acknowledgments

Some valuable photographs of one building under construction in which RIVER TOUGH was applied were kindly offered by Takenaka Co. We wish to express our appreciation for permission to use their photographs.

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