UDC 669 . 14 . 018 . 292 - 413 : 691 . 714

Development of High HAZ Toughness Steel Plates for Box Columns with High Heat Input Welding

Akihiko KOJIMA*[1] Ken-ichi YOSHII*[2]
Tomohiko HADA*[3] Osamu SAEKI*[4]
Kazutoshi ICHIKAWA*[5] Yuzuru YOSHIDA*[6]
Yasumi SHIMURA*[7] Kiyosaburo AZUMA*[1]

Abstract

For safety against earthquakes and for highly efficient welding in high-rise building constructions, high HAZ toughness steel plates have been developed. Based on the new technology for HAZ microstructure refinement, HTUFF®, and by optimizing chemical compositions of steel, BT-HT355C-HF and BT-HT440C-HF steel plates possessing high-performance of HAZ toughness have been commercialized. High heat input welded joints of box columns made of the developed steel plates, joined by electroslag welding or submerged arc welding with high efficiency, had excellent HAZ toughness of more than 70J at 0℃. The weld metal had also good toughness by using newly developed welding materials matched to the developed steel plates.

1. Introduction

In recent years, research relating to the fracture performance of buildings is advancing due to the hard-learned lessons of the Hanshin-Awaji earthquake. We have witnessed a greater demand in toughness against fracture than has conventionally been demanded on the welding portions of the steel frames in buildings[1)]. For example, announcements have been made for buildings demanding high Charpy absorbed energy of the level of 70J at 0°C on the welding portions of the steel frames that are used in high-rise buildings[2)]. On the other hand, there been great demands for high strength and large thickness of the steel plates used in buildings that accompany higher structures and larger spans. There has also been a great demand for highly efficient welding processes in manufacturing of the steel frames. An example of highly efficient welding can be provided in high heat input welding such as electroslag welding (ESW), or multi-electrode submerged arc welding (SAW) that are applied to the diaphragm welding or corner welding of 4-sided box columns. The welding heat input can sometimes be between 50 to 100 kJ/mm.

If this high heat input welding is applied to conventional steel plates for the steel frames, the microstructure of the heat affected zone (HAZ) becomes notably coarse and the toughness of the HAZ is greatly degraded. Thus, there has been a great demand for the development of steel plates that can maintain high HAZ toughness even if high heat input welding is applied thereto. To respond to that demand, a high HAZ toughness steel plate for box columns used in buildings was developed[3-5)] by Nippon Steel Corporation by applying a new "HTUFF (Super High HAZ Toughness Technology with Fine Microstructure Imparted by Fine Particles)"[6,7)].

2. Concept of The Development

2.1 Concept of the development of high HAZ toughness steel plates

See **Table 1** for details relating to the development targets of high HAZ toughness steel plates for box columns. The steel plates are equivalent to the standards of SN490C, BT-HT325C, BT-HT355C,

*[1] Steel Research Laboratories
*[2] Kimitsu Works
*[3] Oita Works
*[4] Nagoya Works
*[5] Oita R&D Lab.
*[6] Plate Sales Division
*[7] Construction and Architectural Materials Development and Engineering Service Division

Table 1 Development targets of high HAZ toughness steel pates for box columns

Steel standard	: SN490C, BT-HT325C, BT-HT355C, BT-HT440C, SM520B-SNC
Welding method	: ESW, multi electrodes SAW, etc.
Maximum welding heat input	: Approximately 100kJ/mm
HAZ toughness	: Charpy absorbed energy at 0°C ≥ 70J (average)

BT-HT440C, SM520B-SNC and support ESW and multi-electrode SAW. As the most important target of the HAZ toughness, 70J was set as the average value for the Charpy absorbed energy at 0°C[2]. In this research, from the viewpoint of stably ensuring strength and low yield ratios which are the basic functions of steel plates for buildings, the appropriate amount of C and carbon equivalents are ensured while making efforts to improve HAZ toughness in high heat input welding.

The basic concept behind the improvement of HAZ toughness can be broadly separated into the following three categories. 1. Refinement of effective grain size; 2. Reduction of the brittle micro phases which are the initiation site for fracture; and 3. Enhancement of the matrix toughness. The main cause of brittleness of HAZ in high heat input welding is the coarse microstructure such as ferrite that transforms at the γ grain boundary, as the initiation site for the brittle fracture. Therefore, from the viewpoint of the first category the refinement of the coarse microstructure is effective in improving toughness. For that reason, reducing the size of the γ grains is an effective means, as can be seen in the this section of this publication entitled “Super High HAZ Toughness Technology with Fine Microstructure Imparted by Fine Particles.”[4] In this research, HTUFF was used to refine and disperse oxides and sulfides in the steel. This held the γ grains in HAZ near the fusion line in high heat input welding to below conventional sizes, as a result the microstructure that transforms at γ grain boundary is refined, thereby HAZ toughness is improved.

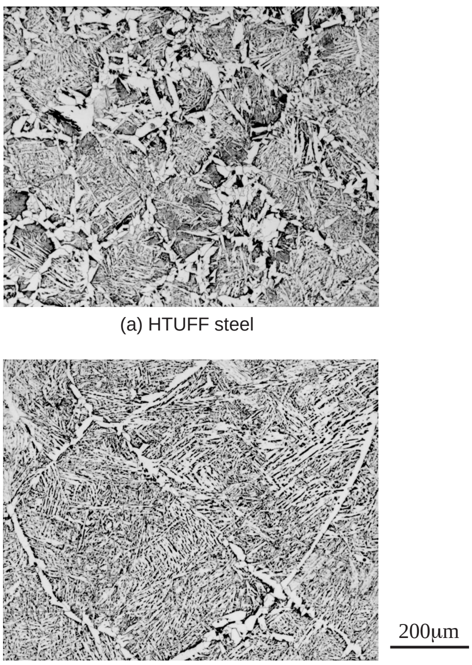


Fig. 1 Simulated HAZ microstructure of BT-HT355C class steels corresponding to ESW (equivalent heat input : 70kJ/mm, reheated peak temperature : 1400°C)

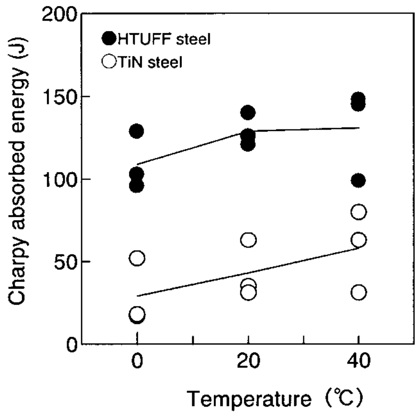


Fig. 2 Simulated HAZ toughness of BT-HT355C class steels corresponding to ESW(equivalent heat input : 70kJ/mm, reheated peak temperature : 1400°C)

In order to investigate the effects when HTUFF is applied to the conventional BT-HT355C class steel, conventional steel (TiN steel) and HTUFF steel were manufactured and applied with a heat history that simulated HAZ near the fusion line of ESW for which the welding heat input is 70kJ/mm. **Fig. 1** and **2** show the simulated HAZ microstructure and toughness of both types of steel. the γ grain coarsening was notably retarded by the application of HTUFF and the refinement of the grain boundary ferrite also was confirmed to have dramatically improved toughness. Based on the effect of HTUFF, high HAZ toughness steel plates for box columns were developed.

2.2 Concept of the development of welding materials

It is necessary to develop welding materials that support these high HAZ toughness steel plates, and to ensure high toughness for the entire joint including the weld metal portions. **Fig. 3** shows the

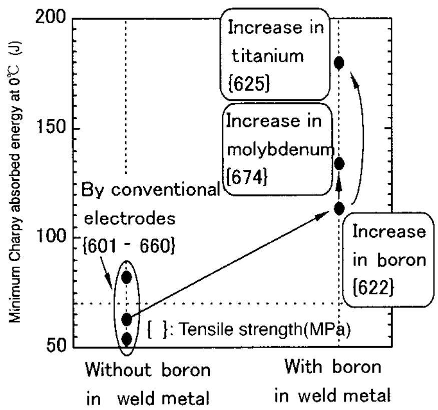


Fig. 3 Effect of alloy elements on mechanical properties of ESW weld metal of BT-HT355C developed steel

resulting alloy elements in the mechanical properties of the ESW weld metal of the steel plate that was developed (BT-HT355C)[8]. It was verified that toughness was improved by optimizing the amount of Mo, Ti, and B which become mixed therein from the welding wire. This was to suppress the formation of coarse grain boundary ferrite by optimizing the chemical compositions hardenability of the weld metal, and refine the microstructure. In the same way, the welding wire and bond type flux which are appropriate for the 2-electrode SAW were studied and the toughness was improved by optimizing the amount of C and Mo of the weld metal[9]. In this research, developments were also made for welding materials that conform to the high HAZ toughness steel plates based on this knowledge.

3. Performance of The Developed Steel Plates

This section describes the performance of these steps to develop steel plates that were commercialized as BT-HT355C-HF, and BT-HT440C-HF, and introduces welded joint performance that was created using welding materials those conform to that develop steel plates[10]. Other than these products, Nippon Steel Corporation also has a lineup of high HAZ toughness steel plates for use as steel frames in buildings corresponding to the standards outlined in Table 1[10].

3.1 Steel plate performance

3.1.1 Chemical composition

See **Table 2** for chemical compositions of the developed steel plates. From the viewpoint of stably ensuring strength and low yield ratios, thought was given to ensuring the proper amount of C and carbon equivalents.

From the viewpoint of high heat input welding HAZ toughness, C was decreased more than conventional steel plates while increases were made to compositions such as Mn, Cu, and Ni as a compensation for the strength for the amount of C that was decreased. With regard to BT-HT440C-HF, adjustments were made to the chemical compositions from the viewpoint of suppressing the formation of MA (martensite austenite constituent) which is the micro brittle phase. HTUFF was applied to the above basic compositions by appropriately mixing Mg and Ca into the steel to refine and disperse the oxides and sulfides.

3.1.2 Mechanical properties

Combining to heat treatment with TMCP (thermo-mechanical control process), 50 mm thick BT-HT355C-HF steel plates and 60 mm thick BT-HT440C-HF steel plates were manufactured. See **Table 3** for the mechanical properties of the developed steel plates. Both steel plates satisfied standards for strength, elongation, low yield ratios, through-thickness properties and toughness.

3.1.3 Weldability

A y-groove cracking test (JIS Z 3158) was performed. Welding cracks did not occur at the preheated temperature of 25°C on either types of steel[10]. Also, a maximum hardness test in weld heat-affected zone (JIS Z 3101) was. The maximum hardness of both types of steel was less than 300 Hv at the preheated temperature of 25°C[10]. Thus, it was confirmed that the developed steel plates have good quality weldability.

3.2 Welded joint performance

3.2.1 Manufacturing of test column

A 3 m long, 4-sided box column was manufactured using the steel was developed. Two types of columns were manufactured using the steel plates developed as having the same standards as skin plates and diaphragms. One type was a BT-HT355C-HF column (beam flange: SN490B); the other was a BT-HT440C-HF column (beam flange: BH-HT440C).

A single pass ESW was applied to the diaphragm welding of the column. A single pass 2-electrode SAW was applied to the corner welding of the column. A multi path gas metal arc welding (GMAW) was applied to the column and beam flange welding. New welding materials[11] that conform to the new develop steel plates were used. **Table 4** shows the welding conditions; **Fig. 4** shows the specimen retrieval positions and V-notch positions in the Charpy impact tests in the welded joints.

Table 2 Chemical compositions of developed steel plates (mass %)

Steel	C	Si	Mn	P	S	Others	HTUFF	Ceq	Pcm
BT-HT355C-HF	0.12	0.26	1.50	0.008	0.002	Nb,Ti	Treated	0.39	0.21
BT-HT440C-HF	0.10	0.16	1.56	0.006	0.002	Cu, Ni, Nb, V, Ti	Treated	0.39	0.23

Ceq=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14
Pcm=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Table 3 Mechanical properties of developed steel plates

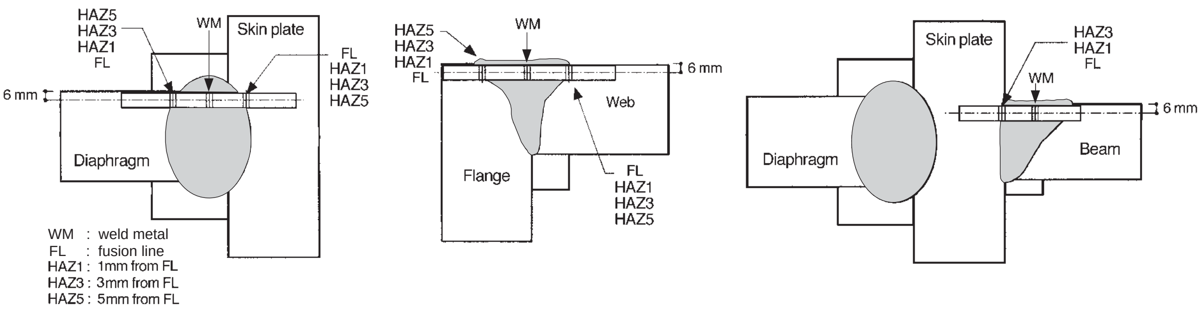
Steel	Thickness (mm)	Direction	Tensile properties 1/4 thickness position				Charpy properties 1/4 tickness position	Through-thickness properties	
			Yield point (N/mm^2)	Tensile strength (N/mm^2)	Elonga-tiom (%)	Yield ratio (%)	$_vE_0$ min/av. (J)	Tensile strength (N/mm^2)	Reduction of area (%)
BT-HT355C-HF	50	L	450	574	32	78	298/302	564, 564, 562	77, 77, 76
		T	451	579	26	78	220/252		
BT-HT440C-HF	60	L	468	610	31	77	251/254	607, 615, 610	69, 74, 75
		T	466	603	32	77	234/236		

L : longitudinal, T : transverse

Table 4 Welding conditions of box columns

Steel for column	Welding portion	Welding method	Welding conditions				
			Current (A)	Voltage (V)	Speed (mm/min)	Heat input (kJ/mm)	Welding material
BT-HT355C-HF	Column diaphragm	ESW/single pass	380	51	14.3	81.4	YM-55HF
BT-HT440C-HF	Column diaphragm	ESW/single pass	380	51	11.6	100.4	YM-55HF
BT-HT355C-HF	Column corner	SAW/single pass	L 2100	36	230	41.0	Y-DLHF
			T 1700	48			NSH-53HF
BT-HT440C-HF	Column corner	SAW/single pass	L 2200	37	200	50.3	Y-DLHF
			T 1800	48			NSH-53HF
BT-HT355C-HF	Column-beam	GMAW/multi passes	380	40	220/450	2.0/4.0	YGW18/21HF
BT-HT440C-HF	Column-beam	GMAW/multi passes	360	41	220/450	2.0/4.0	YGW18/21HF

L : leading electrode, T : traling electrode



(a) Column diaphragm joint (b) Column corner joint (c) Column-beam joint

Fig. 4 Positions of V-notches and specimens of Charpy impact tests in welded joints of box columns

3.2.2 Joint performance

(1) Joint macro-appearance

Fig. 5 shows the macro appearance of the ESW joint and the SAW joint using the BT-HT355C-HF column as an example.

(2) Joint toughness

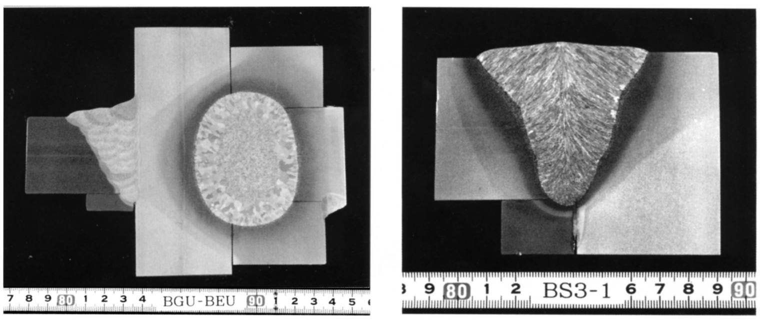
Fig. 6 shows the average value of the Charpy absorbed energy for the joint toughness of the 4-sided box columns. All joints on the two types of columns achieved good quality toughness that successfully satisfies development targets. Good quality toughness that exceeds the target level of 70J for FL (fusion line) and HAZ1 (the HAZ separated 1 mm from the FL) of the ESW joints and SAW joints were achieved as planned. WM (weld metal) toughness was also good quality by using the appropriate welding materials.

(3) Joint strength

Weld metal tensile tests of the ESW joints, SAW joints, and GMAW joints and ESW cross shaped joint tensile tests were conducted. All joints on both types of columns had achieved[10] a thorough strength satisfying the base metal standards. The ruptured position of the ESW cross shaped joint tension tests was on the beam flange base metal.

(4) Joint microstructure

Figs. 7 and 8 shows the microstructure of the ESW joint and the SAW joint using the BT-HT440C-HF column as an example. Regardless of the application of high heat input welding, both joints



(a) Column diaphragm joint and column-beam joint (b) Column corner joint

Fig. 5 Welded joint macrostructure of BT-HT355C-HF column

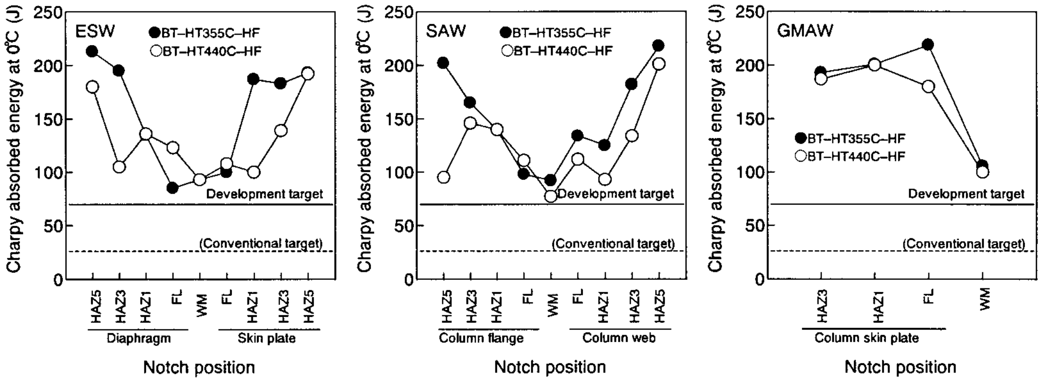


Fig. 6 Welded joint toughness of box columns

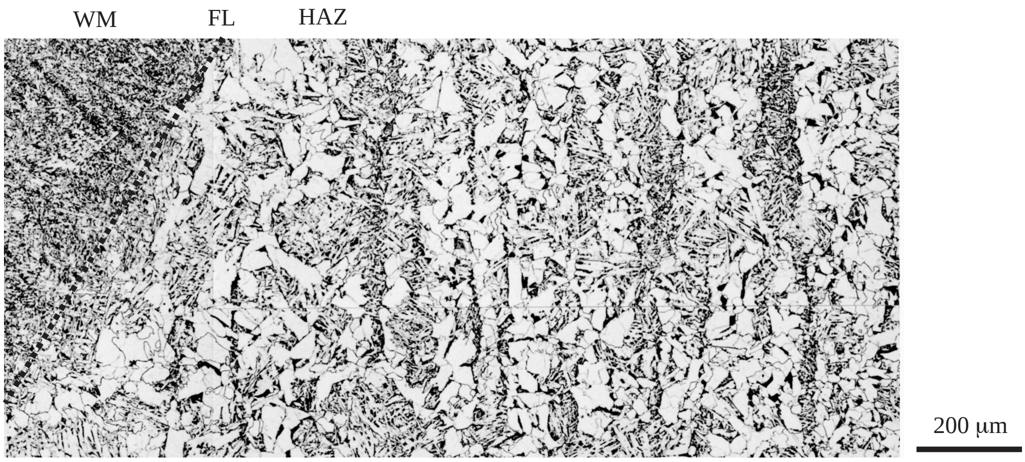


Fig. 7 EWS joint microstructure of BT-HT440C-HF column (skin plate side HAZ of diaphragm joint)

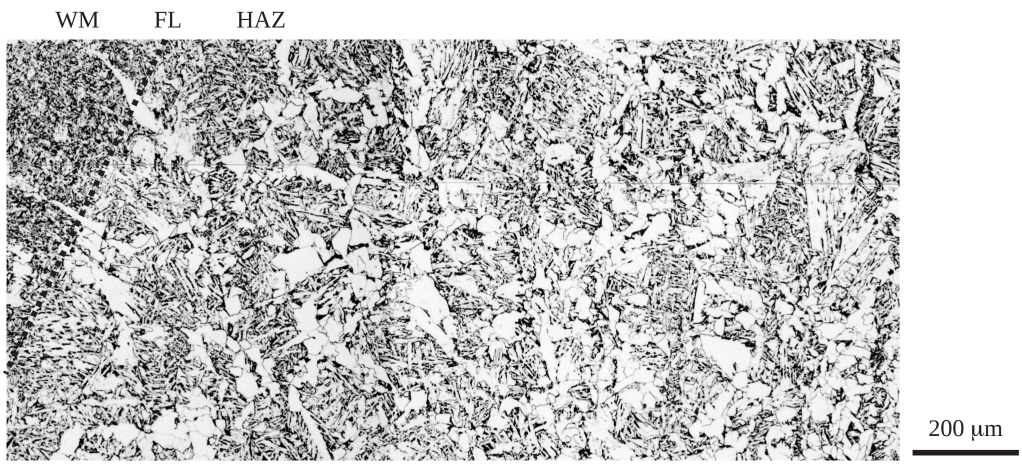


Fig. 8 SAW joint microstructure of BT-HT440C-HF column (flange side HAZ of corner joint)

were confirmed to have notably refined HAZ microstructure near the fusion line because of the effects of HTUFF. Also, in the same way for the BT-HT355C-HF column, the developed steel plates showed good quality high heat input HAZ toughness. This is attributed to the effects of a refined microstructure.

4. Conclusions

High HAZ toughness steel plates for use as steel frames in buildings were developed to support high heat input welding. These were achieved by the application of HTUFF and by the optimizing of chemical compositions of steel. Good quality toughness was achieved which exceeds the Charpy absorbed energy average value of 70J at

0°C on the high heat input welded joints on the 4-sided box columns which were manufactured by combining the develop steel plates (BT-HT355C-HF and BT-HT440C-HF) and welding materials that support them. To date, approximately 6,000 t of the developed steel plates have been shipped for the 4-sided box columns for use in high-rise buildings beginning with the planned C tower (temporary name) located at Marunouchi 1-1[2]. It is believed that the demand for this developed steel plates which satisfy the needs for safety in earthquakes and for highly efficient construction for high-rise buildings, will dramatically increase in the future.

References

1) Guidelines for Preventing Brittle Fracture in Beam-end Welded Connections. Building Center of Japan, September 2003, p.39
2) Inada, T. et al.: Strutec. (7), 35 (2002)
3) Kojima, A. et al.: Materia. 42 (1), 67 (2003)
4) Kojima, A. et al.: Shinnittetsu-Giho. (380), 33 (2004)
5) Kojima, A. et al.: Summary of Technical Papers of Annual Meeting, Architectural Institute of Japan. C-1, 2001, p.761
6) Sakurai, K. et al.: Miyaji Technical Report. 18, 53 (2003)
7) Yokoyama, Y. et al.: Strutec. (6), 45 (2003)
8) Ichikawa, K. et al.: Preprints of the National Meetings of Japan Welding Society. 69, 2001, p.176
9) Nakazawa, H. et al.: Preprints of the National Meetings of Japan Welding Society. 71, 2001, p.252
10) Nippon Steel Corporation Catalogue: HTUFF Steel, High HAZ Toughness Steel Plates for Building Constructions
11) Ichikawa, K. et al.: CAMP-ISIJ. 16, 348 (2003)