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A New Proposal of HAZ Toughness Evaluation Method — Part 1: HAZ Toughness of Structural Steel in Multilayer and Single-Layer Weld Joints

A method using single-layer welds is recommended for estimating HAZ toughness

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ABSTRACT. A huge earthquake experienced in Japan led to the establishment of a new guideline to prevent the brittle fracture of building structures in terms of design, construction, and material. For steel, it was suggested to have heat-affected zone (HAZ) toughness of more than 27 or 70 J in the Charpy impact test at 273 K. This paper relates an investigation into a HAZ toughness evaluation method for construction structural steels. The HAZ toughness was examined for both multilayer and single-layer weld joints, and the characteristics of both methods were compared. The points below were the result.

The method with the multilayer weld joints showed relatively high toughness, and it has a possibility to provide data scatter depending on the welding deposition sequence and the notch sampling position. On the other hand, the method with the single-layer weld joints gave lower toughness. It is less affected by the notch sampling position, and it reflects the effect of the carbon equivalent and the welding condition through a change in microstructure. Consequently, the HAZ toughness estimation using the single-layer weld joints has an advantage from the viewpoint of the lower bound toughness evaluation.

Introduction

The catastrophic Great Hanshin Earthquake, which happened in Japan in 1995, brought about serious damage to some building structures (Ref. 1). The Ministry of Construction (presently, the Ministry of Land, Infrastructure and Transport) launched a project in 1996, which was named Development of Structural Safety Improvement Technology Utilizing New-Generation Steel, to prevent such damage in the future. A number of researchers from industry, government, and academia tackled the tough project to establish a method to prevent brittle failure. Through research work, the idea that structural steel, including its HAZ, should have adequate toughness has become common (Ref. 2). In the guideline (Ref. 3) announced by the Building Center of Japan in 2003, a new criterion was provided from the perspective of design, fabrication, and material. For steel, it demanded 27 or 70 J in ${}_{v}E_{273}$ (absorbed energy at 273 K in the Charpy impact test) to the HAZ toughness in the beam-to-column connection, depending on the design.

Although the standard for structural steel, JIS G 3136 SN Steel (Ref. 4), prescribes the base metal toughness to exceed 27 J in ${}_{v}E_{273}$, the HAZ toughness was not specified. Also, the actual level was uncertain. Utilizing SN steel, it is very important to establish the evaluation method and to clarify the HAZ toughness level. Additionally, since it is impractical to evaluate HAZ toughness for the weld joints of all steel plates used for building structures, the formulation of the relationship between HAZ toughness and chemical compositions seems to be useful.

In this Part 1, methods for assessing HAZ toughness are examined. Two welding methods, multilayer welding and single-layer welding, were conducted, and the characteristics were compared. We focused on the beam-to-column connection, because it is considered the area of most concern for brittle failure under earthquake conditions.

The measurement of the actual toughness level and the formulation of the relationship between HAZ toughness and chemical compositions will be detailed in Part 2.

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KEYWORDS

Earthquake
Brittle Fracture
Gas Metal Arc
Heat-Affected Zone
Structural Steel
Impact Toughness
Charpy

Experimental Procedure

Two types of welding processes, multilayer gas metal arc welding with CO_2 and single-layer gas metal arc welding with CO_2, were compared from the viewpoint of evaluating the HAZ toughness of the beam-to-column connections. Six steel plates and H-sections were used for both tests. Chemical compositions, C_{eq}, P_{CM}, type of products (Plate/H-section), thickness, and toughness (${}_{v}E_{273}$) of the base metal are listed in Table 1.

Multilayer gas metal arc welding with CO_2 was performed on single-bevel grooves with 35-deg angle and with 7 to 10 mm in the root opening. Combinations of heat input, preheating, and interpass temperatures were set as 2 kJ/mm, 423 K (Condition A) and 4 kJ/mm, 623 K (Condition B). As for the welding wire, JIS Z 3312 YGW-18 (Ref. 5) was used for SN490, while JIS Z 3312

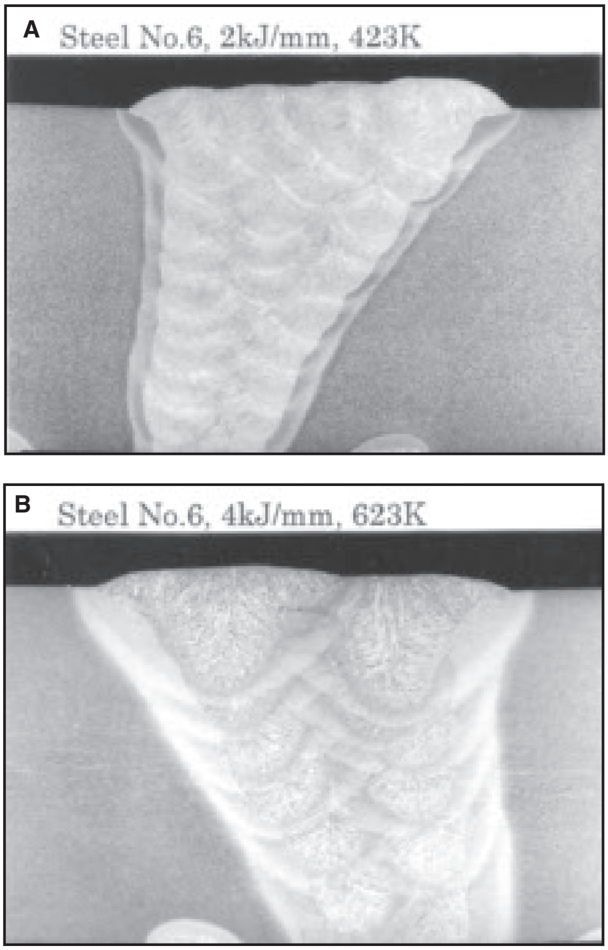

Fig. 1 — Macrostructures of the multilayer weld joints. A — steel No. 6, 2 kJ/mm, 423 K; B — steel No. 6, 4 kJ/mm, 623 K.

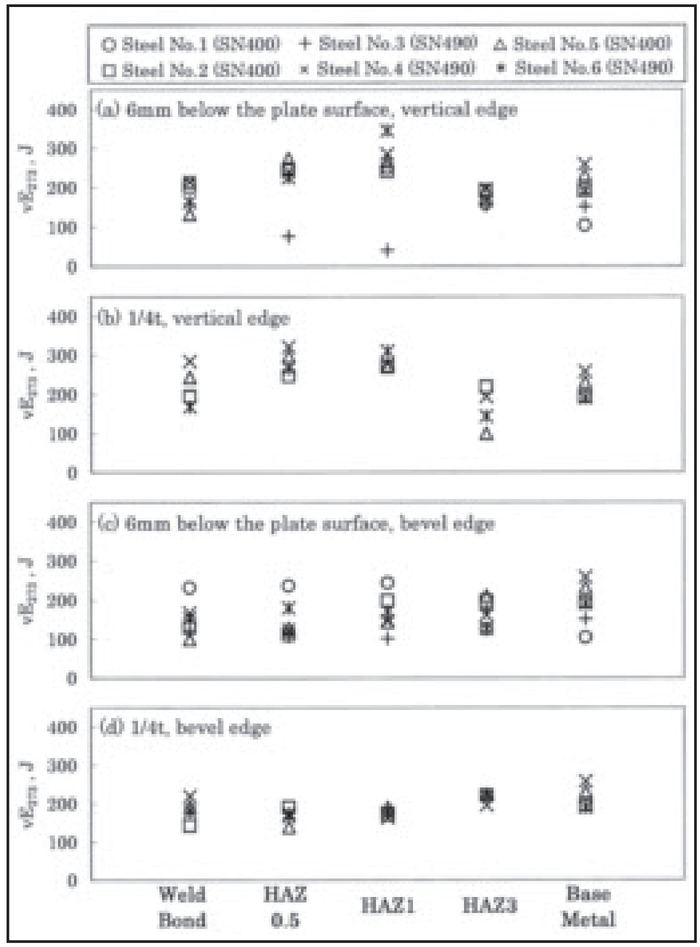

Fig. 2 — Heat-affected zone toughness of multilayer weld joints (2 kJ/mm, 423 K. HAZx means the position at the distance x in mm from the weld interface).

YGW-11 (Ref. 5) was used for SN400.

Charpy impact specimens were machined in such a way that the longitudinal direction of the specimens and the notch root line were perpendicular to the welding direction. The notch root positions were set as the weld interface, HAZ0.5, HAZ1, HAZ3, and HAZ5, in which HAZx means the point at the distance of x (mm) from the weld interface. The sampling positions in the thickness direction were 6 mm below the plate surface and quarter thickness (¼t) to clarify the effect of the presence or absence of the heat cycle due to following weld passes. As for H-sections, the sampling at ¼t was not performed because of the thinness of the section (22 to 28 mm). Additionally, the test specimens were sampled from both the perpendicular edge and the bevel edge to compare the effect of the difference in the weld layers. The Charpy impact tests were carried out at 273 K, and three specimens were used for each condition.

Next, the HAZ toughness of the single-layer weld joints was evaluated to simulate the area that is not affected by the following heat cycle of the multilayer weld joints (Ref. 6). A single-bevel groove, with a depth of 13 mm (not penetrating the plates), a root radius of 5 mm, and an angle of 35 deg was machined. Single-layer gas metal arc welding with CO_2 was performed with combinations of 2 or 4 kJ/mm in heat input and the ambient temperature (no preheating) 423 K, and 623 K in the preheating temperature. Welding wire was the same as for the former test. After single-layer gas metal arc welding, the Charpy test specimens were machined. The relationship between the welding direction and the sampling direction was the same as the former test.

In this test, three aspects were examined. First, the difference in toughness depending on the notch root positions was clarified. The notch root positions were set as the weld, HAZ0.5, HAZ1, HAZ3, and HAZ5. The welding condition was set as 4 kJ/mm in heat input and 623 K in preheating temperature (Condition B). The objective was set as the vertical edge because of the good accordance of the notch root and the weld configuration. The specimens were machined from the area 6 mm below the bead surface.

Next the effect of the heat input and the preheating temperature were examined. The welding conditions were set as 2 kJ/mm and no preheating (Condition C), 2 kJ/mm and 423 K (Condition A), 4 kJ/mm and no preheating (Condition D), 4 kJ/mm and 423 K (Condition E), and 4 kJ/mm and 623 K (Condition B). The notch root position was fixed as HAZ1. The sampling position was 6 mm below the bead surface. The objective weld junction was set as the vertical edge.

Finally, the effect of the sampling position in the thickness direction was confirmed. The sampling position was varied from 6 to 8 mm below the bead surface. The notch root position was fixed as HAZ1. The heat input, the preheating temperature, and the objective weld junction were 4 kJ/mm, 623 K, and vertical edge, respectively.

For all the tests with the single-layer weld joints, the Charpy impact tests were

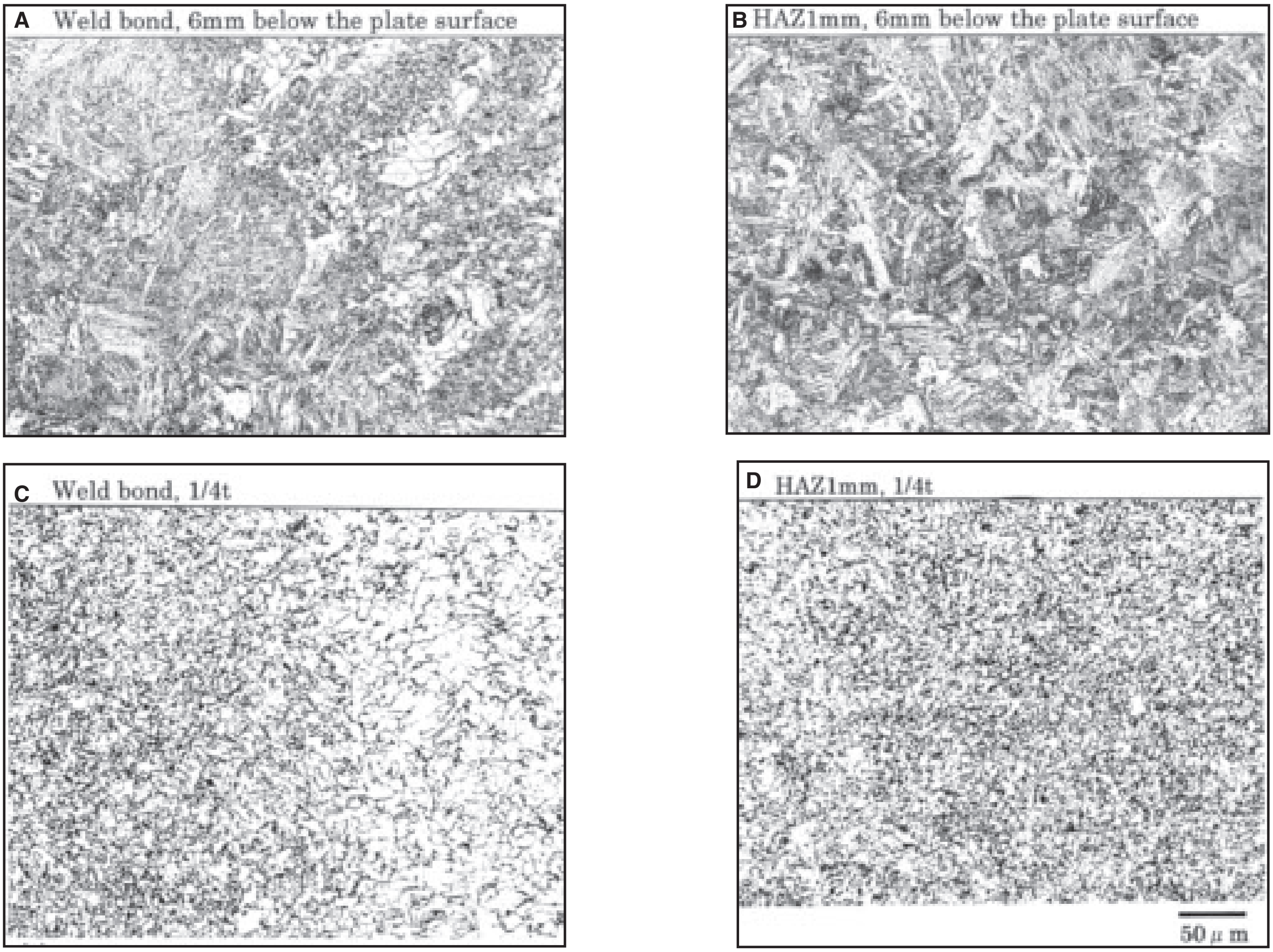

Fig. 3 — Microstructures of the multilayer weld joint (steel No. 6, 2 kJ/mm, 423 K near the vertical edge).

Table 1 — Chemical Compositions and Details of Steels Used (mass %)

Steel No.	Standard	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
1	SN400	0.15	0.21	0.74	0.017	0.012	0.01	0.01	0.02	0
2	SN400	0.13	0.22	0.93	0.010	0.010	0.02	0	0	0
3	SN490	0.16	0.32	1.37	0.025	0.002	0.03	0.02	0.03	0.01
4	SN490	0.15	0.34	1.37	0.014	0.004	0	0.01	0.02	0
5	SN400	0.09	0.23	0.96	0.020	0.007	0.17	0.11	0.12	0.03
6	SN490	0.13	0.28	1.43	0.016	0.005	0.19	0.08	0.12	0.02

Table 1 (continued)

Nb	V	Ti	N	C_{eq}	P_{CM}	Plate or H-section	Thickness (mm)	${}_vE_{273}$ (J)
0.001	0.002	0.002	0.0096	0.29	0.20	H-section	22	104
0	0	0	0.0044	0.29	0.18	Plate	40	193
0	0	0	0.0038	0.41	0.24	H-section	28	151
0	0.040	0	0.0026	0.40	0.24	Plate	40	258
0	0	0	0.0064	0.30	0.17	Plate	40	231
0.010	0	0.003	0.0058	0.41	0.23	Plate	40	191

Note: $C_{eq}=C+Mn/6+Si/24+Mo/4+Cr/5+Ni/40+V/14$ $P_{CM}=C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B$
${}_vE_{273}$: the absorbed energy at 273K by the Charpy impact test. The specimens for the Charpy impact test were machined at ¼t.
Thickness in H-section means the thickness of flange.

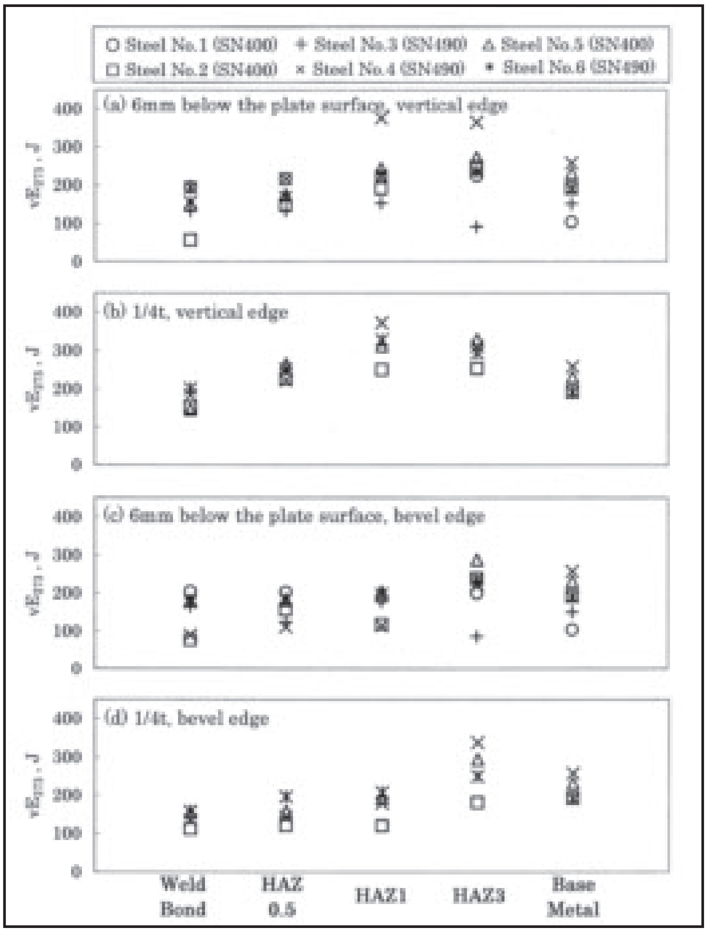

Fig. 4 — Heat-affected zone toughness of multilayer weld joints (4 kJ/mm, 623 K).

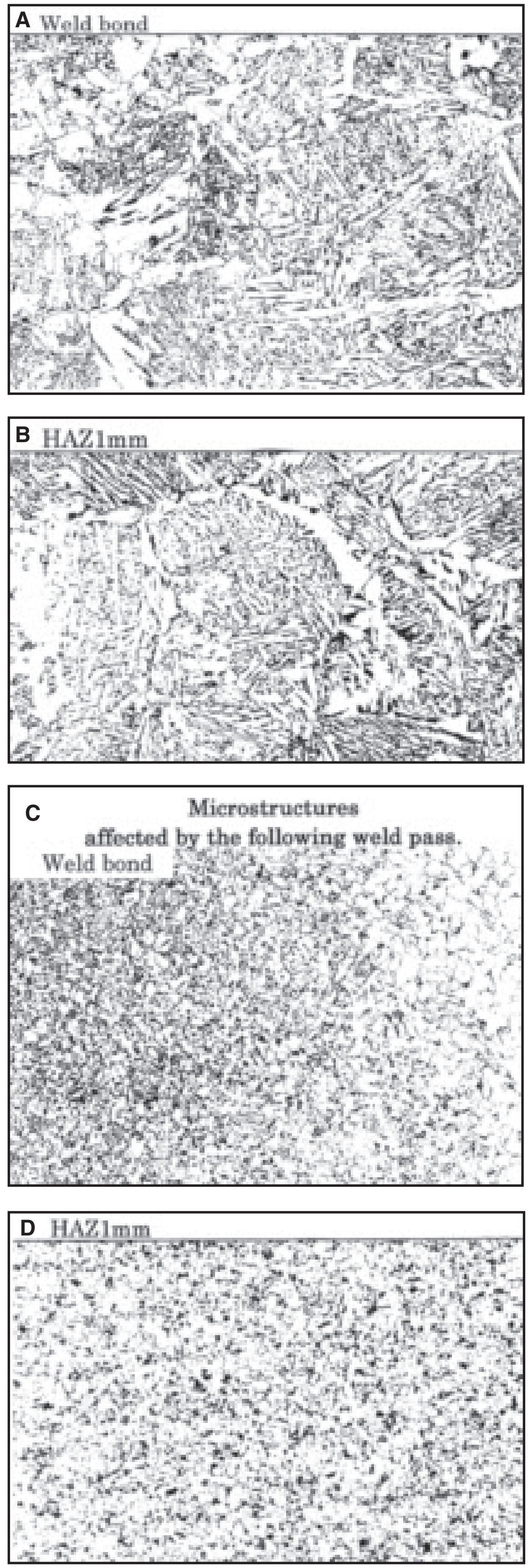

Fig. 5 — Microstructures of multilayer weld joints (steel No. 6, 4 kJ/mm, 623 K, near the vertical edge and 6 mm below the plate surface).

carried out at 273 K, and three specimens were used for each condition.

Results

HAZ Toughness Evaluation with Multilayer Weld Joints

Weld Condition A (2 kJ/mm, 423 K)

An example of cross-sectional macrostructure in the welded joint is shown in Fig. 1A. The relationship between $_{v}E_{273}$ and notch root position is shown in Fig. 2.

While it is well known that the heat cycle with welding often deteriorates HAZ toughness through various mechanisms (Ref. 7), the difference in toughness between base metal and HAZ was small in this experiment. It may be attributed to the reheating by the following welding pass. Examples of HAZ microstructure are shown in Fig. 3A–D. Figure 3A, B shows the coarse microstructures mainly composed of martensite and bainite, and prior-austenite grain size, which was expected to be coarse. It was considered to be formed by heating much above Ac_3 due to the neighboring weld pass, and less affected by the following weld passes. Figure 3C, D shows the microstructures mainly composed of fine ferrite and pearlite. They were expected to transform from the relatively fine austenite made by reheating above Ac_3 with the following weld pass. Because of the lower heat input of 2 kJ/mm, the region, which suffered the effect of the following weld passes, widely existed. This was expected to lead to almost the same toughness in HAZ as that of the base metal.

The HAZ toughness is slightly different depending on the specimen sampling position as was shown in Fig. 2A – D. This difference can be interpreted by the degree of coarsened microstructure remaining. In comparing the position 6 mm below the plate surface and quarter thickness (¼t) (Fig. 2A and B or C and

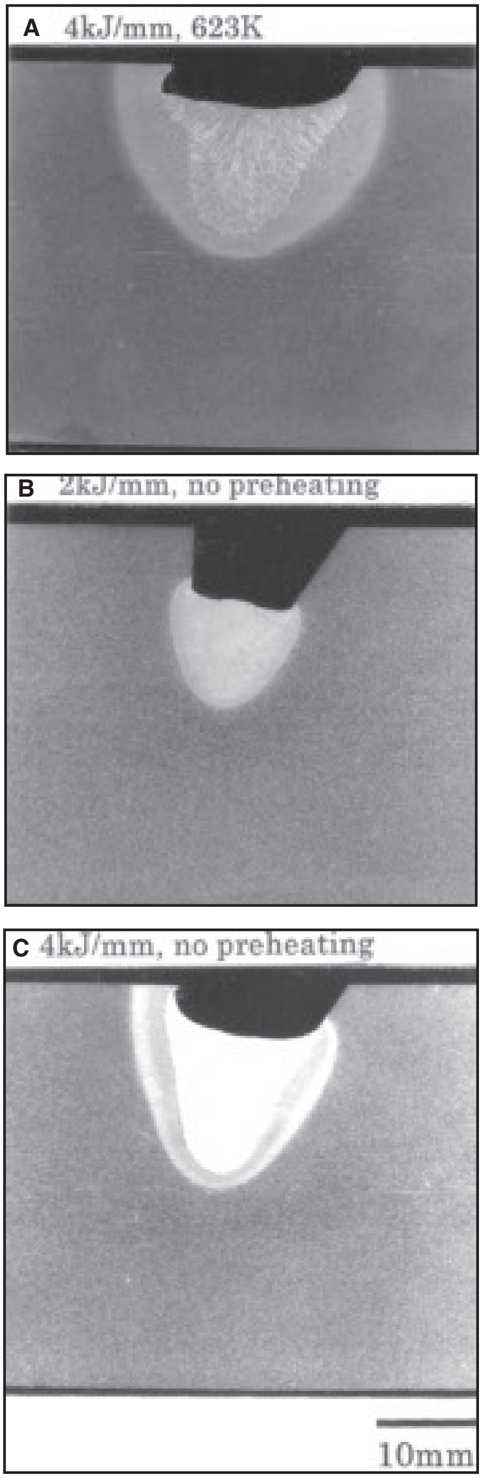

Fig. 6 — Macrostructures of the single-layer weld joints.

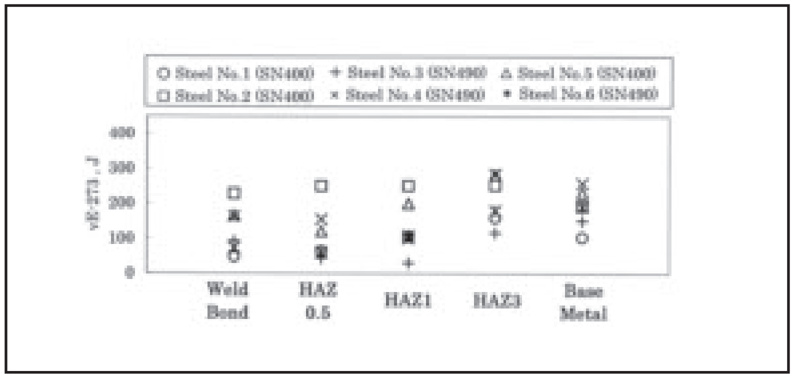

Fig. 7 — Heat-affected zone toughness of the single-layer weld joints (4 kJ/mm, 623 K, 6 mm below the bead surface, vertical edge).

D), the toughness in the former was often a little lower than that in the latter. As most of the weld interface near the plate surface suffers no reheating effect, a lot of coarsened microstructure remains along the weld. Since the region 6 mm below the plate surface includes plenty of coarse microstructure, the toughness was considered to be relatively low. As for the vertical and the bevel edge, the toughness in the latter was often lower than that in the former (Fig. 2A and C or B and D). The number of welding passes per unit length of the weld is smaller in the bevel edge than that in the vertical edge. It means the remaining area of coarsened microstructure is larger in the bevel edge of the weld, and it may lead to lower toughness. Also, the Charpy notch in the bevel edge may also contain weld metal because of the angular weld interface, thus the toughness may be affected by that.

Although the carbon equivalent is quite different between SN400 and SN490 (Table 1), there is no apparent difference in HAZ toughness between them. It means that the chemical compositions do not have the dominating effect on the HAZ toughness in this condition, while the difference in thermal history due to the weld sequence appears to affect the HAZ toughness.

Weld Condition B (4 kJ/mm, 623 K)

An example of macro section is shown in Fig. 1B. Because of the higher heat input, the number of weld passes is apparently fewer than that in weld condition A (2 kJ/mm, 423 K). Relationships between $_vE_{273}$ and the notch root position are shown in Fig. 4. As is the same in welding condition A, the difference in toughness between the HAZ and the base metal was small.

Examples of HAZ microstructures are shown in Fig. 5. Figure 5A and B showsthe microstructures, which are less affected by reheating and are mainly composed of coarse-grain boundary ferrite and bainite. The change in microstructure, compared to condition A, is attributed to the increase in retention time at high temperature and the decrease in cooling rate with the increase in heat input, preheating, and interpass temperature. Figure 5C and D shows the microstructures affected by reheating, which are mainly composed of fine ferrite and pearlite.

As in weld condition A, the toughness 6 mm below the plate surface is often lower than that in the quarter thickness (¼t). It can be interpreted as the degree of refinement of microstructure due to the reheating. As is shown in Fig. 1B, the region, which is not affected by the following weld pass, widely exists 6 mm below the plate surface than that in the quarter thickness.

The fact that the lower toughness appeared in weld condition B rather than in weld condition A is attributed to two points. One is that the microstructure is more coarsened due to the higher heat input, and the other is that the degree of remaining coarsened microstructure is higher because of the smaller number of weld layers per unit length of the weld edge.

Just like the weld condition A, there is no clear relationship between carbon equivalent and $_vE_{273}$.

HAZ Toughness Evaluation Using Single-Layer Weld Joints

Effect of the Notch Root Position

A macro section of the single-layer weld joint in condition B (4 kJ/mm, 623 K) is shown in Fig. 6A. As the weld interface is vertical, it is considered easy to meet the notch root and the coarsened microstructure.

The relationship between $_vE_{273}$ and the notch root position is shown in Fig. 7. The toughness of the weld, HAZ0.5 and HAZ1, was often lower than that of the base metal. Also, the values of HAZ toughness were relatively smaller than those in the multilayer weld joints, and the lower bound value was 48 J, 227 J, 31 J, 100 J, 121 J, and 61 J, respectively for Steel No. 1 to No. 6. As a whole, the difference of HAZ toughness between SN400 and SN490 was explicit compared to the mul-

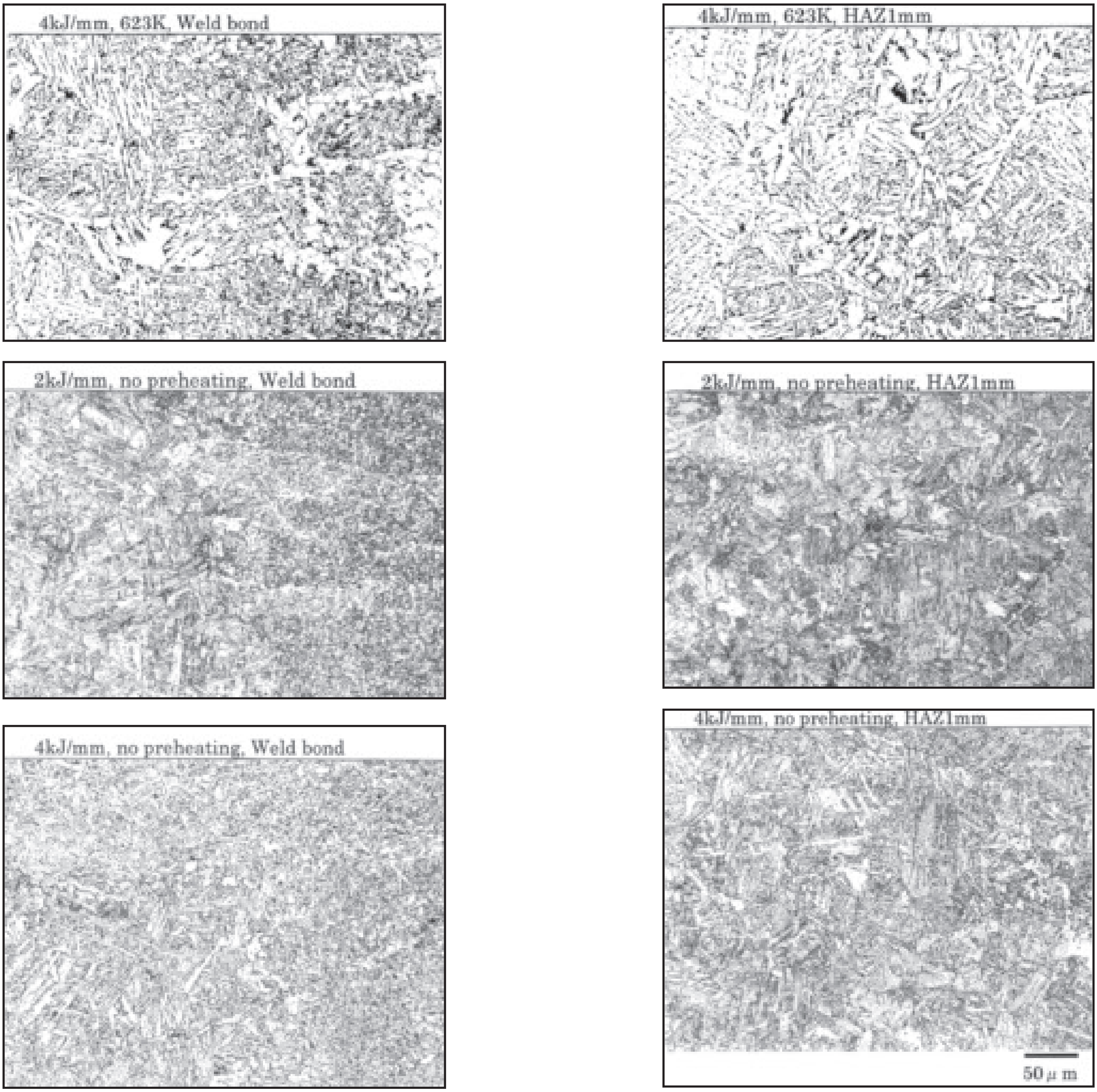

Fig. 8 — Microstructures of the single-layer joint (steel No. 6, near the vertical edge and 6 mm below the bead surface).

tilayer weld joint.

The HAZ microstructures are shown in Fig. 8A and B. Near the weld, the coarsened microstructure, mainly composed of grain boundary ferrite and upper bainite, was observed. Since there is no reheating effect, a coarsened microstructure exists along the bond. It is expected to be the cause of low toughness. Examples of the hardness distribution are shown in Fig. 9A. Although the microstructural component was similar in all the steels used, the hardness of SN490 was relatively higher than that of SN400 due to the higher carbon equivalent. Its difference corresponds to the HAZ toughness deterioration in SN490.

Effect of the Welding Condition

Examples of macrostructure in the welding condition C (2 kJ/mm, no preheating) and D (4 kJ/mm, no preheating) are shown in Fig. 6B and C. The relationship between $_vE_{273}$ and the weld conditions is shown in Fig. 10. While the values of HAZ toughness in all conditions were low, especially those in the condition C and B (4 kJ/mm, 623 K) were relatively lower. Furthermore, the effect of carbon equivalent is definitive, and $_vE_{273}$ in SN490 was often lower than in SN400.

Examples of HAZ microstructure are shown in Fig. 8C to F. Hardness distributions in weld conditions C and D are shown in Fig. 9B and C. As for the weld condition C (2 kJ/mm, no preheating), the austenite grain size was not expected to be so coarse because of the short time at high temperature, but the cooling rate was so

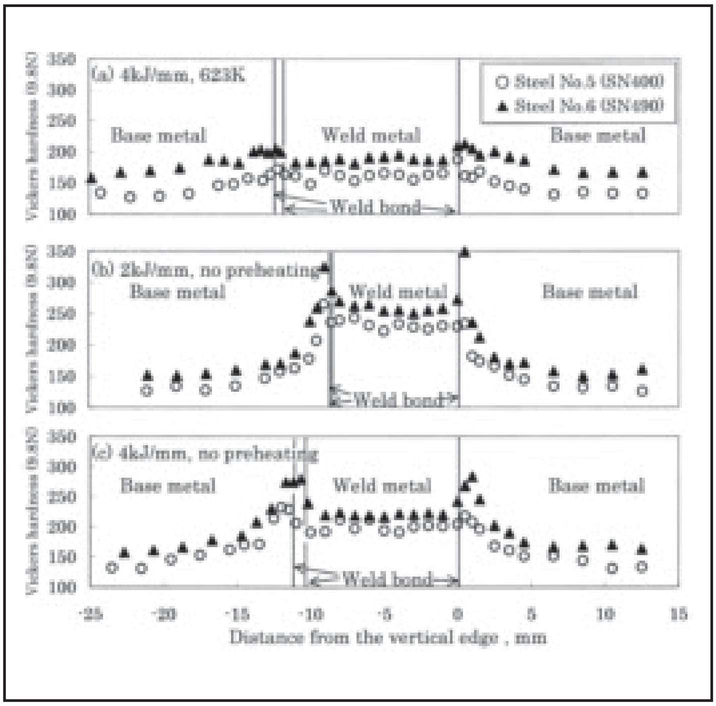

Fig. 9 — Hardness distribution of the single-layer weld joints. A — 4 kJ/mm, 623 K; B — 2 kJ/mm, no preheating; C — 4 kJ/mm, no preheating.

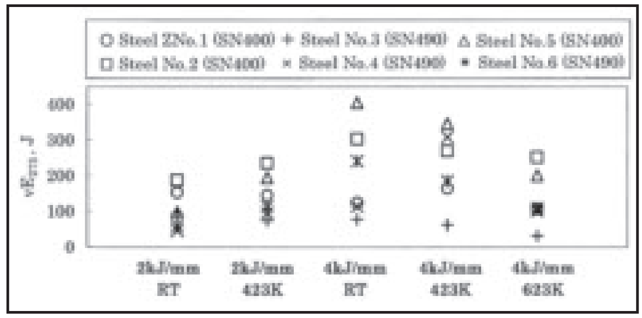

Fig. 10 — Heat-affected zone toughness of single-layer weld joints (6 mm below the bead surface, HAZ1, vertical edge).

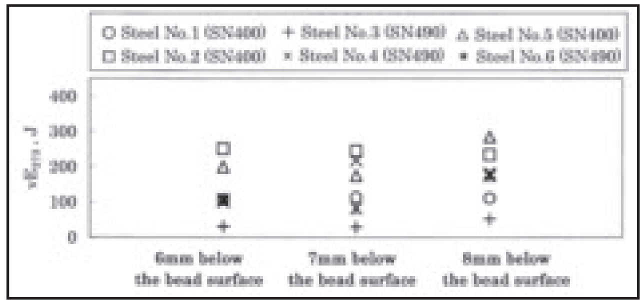

Fig. 11 — Heat-affected zone toughness of single-layer weld joints (4 HkJ/mm, 623 K, HAZ1, vertical edge).

large that the austenite transformed to a hard microstructure, mainly composed of martensite. The maximum HAZ hardness attained was 349 HV in steel No. 6. It is considered to be the cause of the low toughness.

On the other hand, the maximum HAZ hardness in weld condition B (4 kJ/mm, preheating of 623 K) was 212 HV in Steel No. 6, because the cooling rate was not so high due to the high heat input and the high preheating temperature. In this case, the deterioration of HAZ toughness is attributed not to the hardness but to the coarse microstructure.

Meanwhile, in weld condition D (4 kJ/mm, no preheating), the tendency for austenite grain coarsening is not remarkable, and the cooling rate is smaller than in condition C, so the microstructure is not so hard and not so coarsened, which was the reason for the relatively high HAZ toughness.

Since the dependence of the microstructure on the welding condition was common for all the steels used, the deterioration of HAZ toughness can be explained by the increasing hardness in the low heat input and the coarsened microstructure in the high heat input and high preheating temperature (Refs. 8, 9).

Effect of the Sampling Position in Thickness Direction

The relationship between $_{v}E_{273}$ and the sampling position in thickness direction is shown in Fig. 11. The variation of toughness based on the sampling position was small. This is attributed to the presence of similar coarse microstructure in the vicinity of the weld bond. In other words, the effect of sampling position becomes small in the absence of the following heat cycle.

Discussion

The characteristics of HAZ toughness evaluation with both weld joints are discussed. As a whole, the values of HAZ toughness in the multilayer weld joints were high, and they were almost the same as those in the base metal. The dominating factor in HAZ toughness is expected as the amount of coarsened microstructure and the degree of coarsening. Also, there is no clear relationship between HAZ toughness and the carbon equivalent.

Those results indicate that HAZ toughness estimation using the multi-layer weld joint has a possibility to provide data scatter depending on the weld deposition sequence and the sampling position of specimens.

In addition, even if the specimen is sampled from the region that is mainly composed of coarsened microstructure, the mismatch of the notch root and the weld interface may lead to the loss of the actual lower bound HAZ toughness.

On the other hand, the HAZ toughness values in the single-layer weld joints were lower than those in the multilayer weld joints. While the toughness in the multilayer weld joints was affected by the position of the sampling through the degree of remaining coarsened microstructure, the toughness in the single-layer weld joints is not affected by the sampling position and it reflected the characteristics of the microstructure, as was shown in the dependence of HAZ toughness on the carbon equivalent and the welding condition. Consequently, the HAZ toughness estimation using the single-layer weld joint has an advantage from the viewpoint of the reflection of the material and the weld condition, and of the lower bound toughness evaluation.

Conclusions

The HAZ toughness in beam-to-column connections of structural steel (SN steel) and methods of toughness evaluation were investigated. The results are as follows:

1) The method with the multilayer weld joints shows relatively high toughness, and it has a possibility to provide data scatter depending on the weld deposition sequence and the sampling position of the Charpy specimens.

2) The method with the single-layer weld joints gives lower toughness, and it is less affected by the sampling position. It reflects the effect of the carbon equivalent and the welding condition.

3) The experimental method to esti-

mate the toughness of coarsened microstructure in the HAZ of structural steel was the one using the single-layer weld joints. It is expected to give the conservative and fair result. The reason is that it is easy to meet the coarsened microstructure with the notch root of the specimen, and also it is less affected by the weld deposition and the sampling position.

Acknowledgment

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