A New Proposal of HAZ Toughness Evaluation Method: Part 2 — HAZ Toughness Formulation by Chemical Compositions

The HAZ toughness levels were measured and a relationship was established with the chemical compositions of structural steels

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ABSTRACT. This paper details an investigation into the measurement and the prediction of heat-affected zone (HAZ) toughness for construction structural steels. The HAZ toughness was examined using both single-layer and multilayer welded joints, and correlated to the chemical compositions of the steels used. From the series of the tests, the parameter, f_{HAZ}, was derived to assess approximately whether a steel plate has adequate HAZ toughness. The condition is shown below.

$f_{HAZ} \le 0.577$ for ${}_vE_{273}$ (single layer) $\ge$ 30J, ${}_vE_{273}$(multilayer) $\ge$ 70J

$f_{HAZ} \le 0.632$ for ${}_vE_{273}$(single layer) $\ge$ 12J, ${}_vE_{273}$(multilayer) $\ge$ 27J

$f_{HAZ} = C + Mn/8 + 6 (P + S) + 12 N - 4 Ti$

(Note: The content of Ti should be considered as 0 when it is equal to or less than 0.005 mass-%.)

Introduction

In Part 1 (*Welding Journal* 86(1): 1-s), the development of the available method to assess HAZ toughness was studied. In Part 2, the residual two issues, the measurement of the actual toughness level and the formulation of the relationship between HAZ toughness and chemical compositions, were examined.

As for the HAZ toughness measurement, both multilayer weld joints and single-layer weld joints were used. As was described in Part 1, the required toughness is more than 27 J or 70 J in ${}_vE_{273}$ (absorbed energy at 273 K by the Charpy impact test). The aim of these tests was to determine if the HAZ toughness of SN steel accommodates the condition.

Regarding the HAZ toughness formulation, a procedure composed of three steps was adopted. First, the formulation of the relationship between the HAZ toughness in the single-layer weld joints and the chemical compositions was conducted. Since the HAZ toughness of the single-layer weld joints is not affected by the weld sequence, a high accuracy of formulation can be expected. Secondly, the relationship in HAZ toughness between the single-layer weld joints and the multilayer weld joints was clarified. Finally, the chemical composition equation to attain the required HAZ toughness level was produced based on the above two formulations.

A lot of study to clarify the effect of chemical compositions on HAZ toughness has been conducted (Refs. 1–13), and it is well known that the effect varies depending on the welding conditions or the chemical compositions of steel used. In this paper, the applicable scope was limited to the beam-to-column connections used in construction design with structural steel such as JIS G 3136 SN steel (Ref. 14).

KEYWORDS

Chemical Composition
HAZ
H-Shapes
Structural Steel
Construction
Toughness

Experimental Procedure

In this paper, a chemical composition condition that attains a certain HAZ toughness level is explained. The condition to attain 27 J or 70 J in HAZ toughness with the multilayer weld joint was examined. Forty-six steel plates and H-sections, including the steels used in the Part 1 investigation, were used. The range of tensile strength was around 400 to 490 N/mm^2. The chemical compositions, JIS standard, type of products, whether industrial-made or laboratory-made, plate thickness, and ${}_vE_{273}$ of the steels used are shown in Table 1.

Similar to the method in Part 1, HAZ toughness was measured using multilayer and single-layer weld joints. Since it was clarified from the former investigation that the toughness in condition B (4 kJ/mm, 623 K) was a little lower than that in condition A (2 kJ/mm, 423 K), the welding condition was decided as 4 kJ/mm in heat input and 623 K in preheating and interheating temperature. The groove configurations, the welding direction, and the wires used were the same as in Part 1. The notch root position was set as HAZ1, because the toughness at this position was lower than those in the other positions, and it is thought important to avoid the effect of weld metal for the regression analysis. Regarding the thickness direction, 6 mm below the plate and bead surfaces were chosen for the multilayer and single-layer weld joints, respectively, because of the lower toughness compared to that in the quarter thickness (¼t). The objective weld location was selected as the vertical edge so that the notch root samples contained as much coarsened microstructure as possible. For each condition, three specimens were tested at 273 K.

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Results

Result of the HAZ Toughness Estimation

Result of the HAZ toughness estimation for the steel plates and H-sections, whose chemical compositions are described in Table 1, is shown in Fig. 1. In the multilayer weld joints, the values for $_vE_{273}$ were more than 27 J, but partly less than 70 J. On the other hand, in the single-layer weld joints, the values for $_vE_{273}$ were usually less than those in the multilayer weld joints, and it was partly less than 27 J.

The relationship in HAZ toughness between the multilayer and the single-layer weld joints is shown in Fig. 2. Since most of the plots exist above the line whose gradient is one, it was confirmed that HAZ toughness of the multilayer weld joint is higher than that of the single-layer weld joint.

HAZ Toughness Formulation by Chemical Compositions

As was explained in Part 1, the degree of remaining coarsened microstructure is changeable in the multilayer weld joints depending on the difference in the welding deposition sequence. Therefore, it is possible to obtain quite different HAZ toughness even in the steel plates with the same chemical compositions, the same welding condition, and the same sampling position with multilayer weld joints. In fact, it is difficult to make clear the relationship between chemical compositions and HAZ toughness in the multilayer weld joints. On the other hand, it is easy to quantify the effect of chemical composition with single-layer weld joints.

So, the effect of chemical compositions on HAZ toughness is quantified using the data of the single-layer weld joints (Step

Table 1 — Chemical Compositions of the Steels Used (unit:mass%)

Steel No.	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	Ti	N	C_{eq}	P_{CM}
1	0.15	0.21	0.74	0.017	0.012	0.01	0.01	0.02		0.001	0.002	0.002	0.0096	0.29	0.20
2	0.13	0.22	0.93	0.010	0.010	0.02							0.0044	0.29	0.18
3	0.16	0.32	1.37	0.025	0.002	0.03	0.02	0.03	0.01				0.0026	0.41	0.24
4	0.15	0.34	1.37	0.014	0.004		0.01	0.02			0.040		0.0026	0.40	0.24
5	0.09	0.23	0.96	0.020	0.007	0.17	0.11	0.12	0.03				0.0064	0.30	0.17
6	0.13	0.28	1.43	0.016	0.005	0.19	0.08	0.12	0.02	0.010		0.003	0.0058	0.41	0.23
7	0.10	0.25	0.46	0.022	0.009	0.35	0.08	0.10	0.01				0.0130	0.21	0.16
8	0.12	0.15	0.83	0.023	0.006	0.22	0.08	0.14	0.04				0.0095	0.30	0.19
9	0.21	0.28	1.19	0.024	0.013	0.01	0.02	0.21	0.09	0.001	0.003	0.002	0.0029	0.49	0.30
10	0.15	0.21	1.29	0.020	0.004	0.10	0.05	0.07	0.02		0.010		0.0088	0.39	0.23
11	0.15	0.10	0.32	0.021	0.017	0.28	0.11	0.08	0.03				0.0104	0.23	0.19
12	0.16	0.24	0.84	0.014	0.011	0.04	0.03	0.02		0.002	0.003	0.001	0.0043	0.32	0.21
13	0.11	0.14	0.63	0.024	0.011	0.26	0.09	0.07	0.02				0.0095	0.24	0.17
14	0.17	0.39	1.43	0.020	0.006		0.01	0.03			0.004		0.0045	0.43	0.26
15	0.17	0.44	1.44	0.024	0.004	0.01	0.01	0.02					0.0022	0.43	0.26
16	0.16	0.26	1.29	0.016	0.005	0.19	0.08	0.11	0.02	0.010		0.002	0.0066	0.42	0.25
17	0.15	0.40	1.55	0.022	0.003	0.03	0.03	0.02		0.009	0.006	0.013	0.0035	0.43	0.24
18	0.17	0.32	1.35	0.016	0.003	0.02	0.02	0.03	0.01				0.0022	0.42	0.25
19	0.16	0.25	1.52	0.017	0.003	0.01		0.02			0.004	0.001	0.0038	0.43	0.25
20	0.16	0.44	1.45	0.016	0.002	0.01	0.01	0.02				0.012	0.0029	0.43	0.25
21	0.15	0.40	1.47	0.016	0.002	0.01	0.02	0.02		0.015			0.0039	0.42	0.24
22	0.13	0.34	1.49	0.018	0.002	0.12	0.05	0.09	0.02	0.012		0.013	0.0050	0.42	0.23
23	0.15	0.28	1.50	0.016	0.004	0.15	0.07	0.16	0.03	0.012		0.003	0.0062	0.45	0.25
24	0.15	0.38	1.54	0.014	0.002	0.03	0.03	0.02		0.009	0.004	0.013	0.0036	0.43	0.24
25	0.16	0.28	1.49	0.012	0.002	0.01	0.02	0.04	0.01	0.010	0.002	0.002	0.0037	0.43	0.25
26	0.17	0.34	1.22	0.010	0.001	0.02	0.03	0.03	0.01				0.0042	0.40	0.25
27	0.15	0.37	1.41	0.011	0.001	0.03	0.03	0.04	0.01				0.0051	0.41	0.24
28	0.15	0.34	1.34	0.013	0.002	0.01		0.02			0.034	0.002	0.0045	0.39	0.23
29	0.14	0.32	1.28	0.005	0.002	0.01		0.02			0.004	0.012	0.0042	0.37	0.22
30	0.12	0.30	1.37	0.015	0.008								0.0050	0.36	0.20
31	0.12	0.29	0.70	0.014	0.007		0.01	0.02					0.0054	0.25	0.17
32	0.12	0.29	1.39	0.016	0.007	0.15		0.10				0.004	0.0047	0.38	0.21
33	0.13	0.29	1.38	0.014	0.008	0.14	0.01	0.08				0.002	0.0106	0.39	0.22
34	0.12	0.28	1.38	0.016	0.007	0.15		0.09				0.004	0.0045	0.38	0.21
35	0.16	0.29	1.38	0.029	0.008			0.01					0.0049	0.40	0.24
36	0.16	0.29	1.40	0.016	0.002		0.02	0.03					0.0047	0.41	0.24
37	0.16	0.29	1.40	0.016	0.014		0.02	0.03					0.0045	0.41	0.24
38	0.16	0.28	1.37	0.014	0.008			0.01		0.009			0..0058	0.40	0.24
39	0.16	0.28	1.38	0.014	0.008			0.01		0.027			0.0062	0.40	0.24
40	0.16	0.30	1.38	0.005	0.008			0.01				0.001	0.0051	0.40	0.24
41	0.16	0.30	1.39	0.010	0.008			0.01				0.001	0.0050	0.41	0.24
42	0.16	0.30	1.38	0.020	0.008			0.01				0.001	0.0050	0.41	0.24
43	0.16	0.30	1.40	0.016	0.008		0.02	0.03				0.001	0.0048	0.41	0.24
44	0.16	0.32	1.41	0.016	0.008								0.0160	0.41	0.24
45	0.16	0.31	1.41	0.016	0.008								0.0160	0.41	0.24
46	0.21	0.29	1.37	0.015	0.008								0.0051	0.45	0.29

C_{eq} = C + Mn/6+Si/24=Mo/4+Cr/5+Ni/50+V/14

P_{CM} = C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B

Note: Steels No. 1 to 6 are the same as those used in part 1 investigation.

The Charpy impact test specimens were machined at 1/4t or in the vicinity of 1/4t.

1). Secondly, an approximate relationship between the toughness of the multilayer and that of the single-layer weld joints in the lower bound toughness region is sought (Step 2). Then, combining these two formulations, the chemical composition formulation to attain a certain HAZ toughness level in the multi-layer weld joint is derived (Step 3).

Formulation of the Relationship between HAZ Toughness of Single-Layer Weld Joints and Chemical Compositions

Step 1

At first, a general expression, which relates toughness to chemical compositions, was assumed. Based on the result of the JWS-APD committee (Ref. 15), which used Nokota's formulation (Ref. 16), the following expression is assumed:

$$ {}_vE_{273}(\text{single layer}) = \frac{300}{\{\exp(-f)+1\}} \tag{1} $$

$$ \begin{aligned} f = {} & a_1 + a_2 \times C + a_3 \times Si + a_4 \\ & \times Mn + a_5 \times (P+S) + a_6 \\ & \times (Cu+Ni) + a_7 \times (Cr+Mo+V) \\ & + a_8 \times Nb + a_9 \times Ti + a_{10} \times N \end{aligned} \tag{2} $$

The term, ${}_vE_{273}$*(single layer)*, means the absorbed energy of the single-layer weld joint in the Charpy impact test at 273 K on the Joule scale, a_1 to a_{10} are coefficients, and the unit of each chemical composition is mass-%. The coefficient, 300, on the right side of Equation 1 corresponds to the upper shelf energy in the Charpy impact test. The range of the upper shelf energy in some steel plates was 250 to 350 J; therefore, the value 300 was employed here. It was confirmed that the change in this coefficient has less effect on the result of the regression analysis. Using formulations 1 and 2, the nonlinear regression analysis was conducted based on the aforementioned data, which are composed of 46 sets of chemical compositions and ${}_vE_{273}$*(single layer)*.

The result of the nonlinear regression analysis is shown in Table 2. The term "coefficient of variation" is the standard error divided by the coefficient. Since a small coefficient of variation means that it has high reliability, the coefficient of C, Mn, (P+S), Ti, and N are expected to have a certain level of reliability. As for Si, (Cu+Ni), (Cr+Mo+V), and Nb, the reliability is thought to be relatively lower.

As is shown in Table 2, the increase of the content such as C, Mn, P, S, and N deteriorates HAZ toughness. For C and Mn, the deterioration is attributed to the increase of hardness or the formation of the brittle phase such as martensite-austenite constituent (MA) (Refs. 2, 3). As for P, it is ascribed as the grain boundary segregation or the increase of brittle phase (Refs. 4–6). According to S, it is on the ground of grain boundary embrittlement (Ref. 7) or the increase of inclusions. As for N, it is considered as the solute embrittlement (Refs. 4, 8, 9). On the other hand, Ti is expected to improve HAZ toughness through the refinement of austenite grain or the decrease of solute N (Refs. 10–12).

The relationship between the experimental value and the calculated value is shown in Fig. 3, and the relationship between ${}_vE_{273}$*(single layer)* and f is shown in Fig. 4. Since the favorable correlation was confirmed, it was considered to be appropriate to estimate ${}_vE_{273}$ from the chemical compositions expression *f*.

Formulation of the Relationship of HAZ Toughness between Multilayer Weld Joint and Single-Layer Weld Joint

Step 2

The relationship of HAZ toughness between multilayer and single-layer weld joints is shown in Fig. 2. As was described thus far, when the degree of the remaining coarsened microstructure is different due to the difference in the weld deposition sequence, the HAZ toughness values of the multilayer weld joints may vary widely, even in the case of almost the same HAZ toughness in the single-layer weld joints. From the viewpoint of adopting the average level in the data scatter, the regression analysis was conducted using the 32 sets of data, assuming the quadratic expression. The result is shown in Fig. 5.

Comparing this curve with each data, the variation of the data is remarkable when ${}_vE_{273}$(multilayer) is higher than 70 J, but it is small when ${}_vE_{273}$(multilayer) is lower than 70 J. Consequently, in the range of the relatively lower toughness of interest, it is considered reasonable to use the average curve for estimating the necessary ${}_vE_{273}$(single layer) to attain 70 J or 27 J in ${}_vE_{273}$(multilayer). The values of 30 J and 12 J in ${}_vE_{273}$(single layer) were calculated for each attainment.

Table 1 — Continued

Standard	Plate or H-section	Factory or Laboratory	Thickness (mm)	${}_vE_{273}$ (base metal) (J)
SN400	H	Factory	22	104
SN400	Plate	Factory	40	193
SN490	H	Factory	28	151
SN490	Plate	Factory	40	258
SN400	Plate	Factory	40	231
SN490	Plate	Factory	40	191
SS400	H	Factory	15	90
SN400	H	Factory	14	165
SM490	Plate	Factory	40	45
SM490	H	Factory	15	127
SS400	H	Factory	15	18
SN400	H	Factory	14	
SN400	H	Factory	15	134
SN490	Plate	Factory	40	129
SN490	Plate	Factory	28	130
SN490	Plate	Factory	25	149
SN490	Plate	Factory	25	311
SN490	Plate	Factory	32	207
SN490	Plate	Factory	25	235
Sn490	Plate	Factory	28	189
SN490	Plate	Factory	40	222
Sn490	Plate	Factory	32	248
SN490	Plate	Factory	40	158
SN490	Plate	Factory	25	314
SN490	Plate	Factory	25	274
SN490	Plate	Factory	28	242
SN490	Plate	Factory	32	227
SN490	Plate	Factory	25	287
SN490	Plate	Factory	25	271
—	Plate	Labo.	22	198
—	Plate	Labo.	22	184
—	Plate	Labo.	22	235
—	Plate	Labo.	22	66
—	Plate	Labo.	22	227
—	Plate	Labo.	22	104
—	Plate	Labo.	22	100
—	Plate	Labo.	22	106
—	Plate	Labo.	22	68
—	Plate	Labo.	22	45
—	Plate	Labo.	22	167
—	Plate	Labo.	22	163
—	Plate	Labo.	22	136
—	Plate	Labo.	22	104
—	Plate	Labo.	22	164
—	Plate	Labo.	22	56
—	Plate	Labo.	22	90

Table 2 — Result of the Nonlinear Regression Analysis

Element	Mark	Coefficient	Standard Error	Coefficient of Variation (%)
(Constant term)	a_1	8.1	1.7	21
C	a_2	–17.6	6.4	–37
Si	a_3	–1.3	2.8	–214
Mn	a_4	–2.3	0.6	–28
(P+S)	a_5	–111.6	26.5	–24
(Cu+Ni)	a_6	0.4	2.4	554
(Cr+Mo+V)	a_7	3.1	3.6	116
Nb	a_8	–44.3	29.1	–66
Ti	a_9	72.8	32.5	45
N	a_{10}	–201.9	86.9	–43

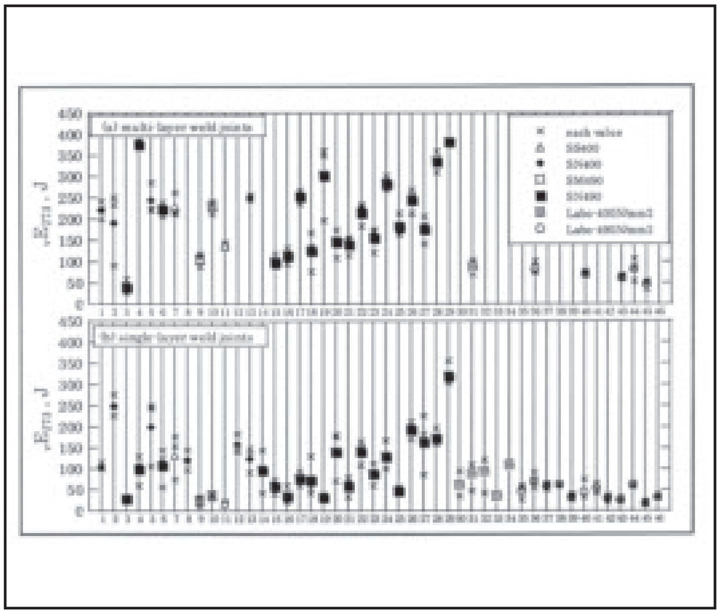

Fig. 1 — Result of the HAZ toughness estimation.

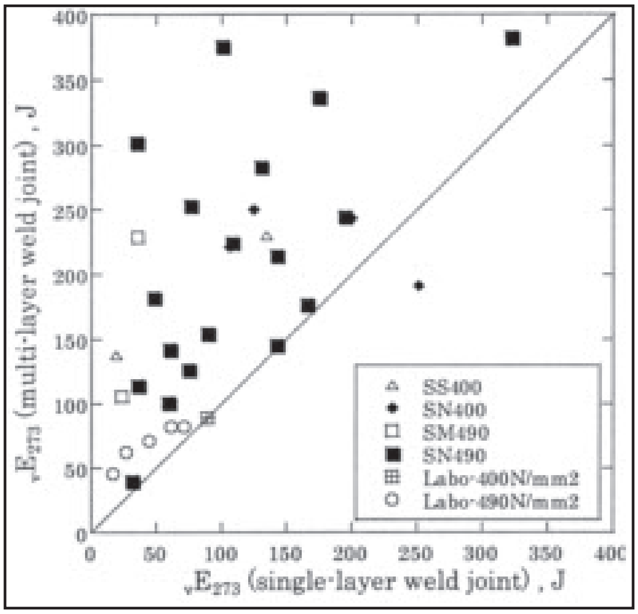

Fig. 2 — Relationship of HAZ toughness between single- and multilayer weld joints.

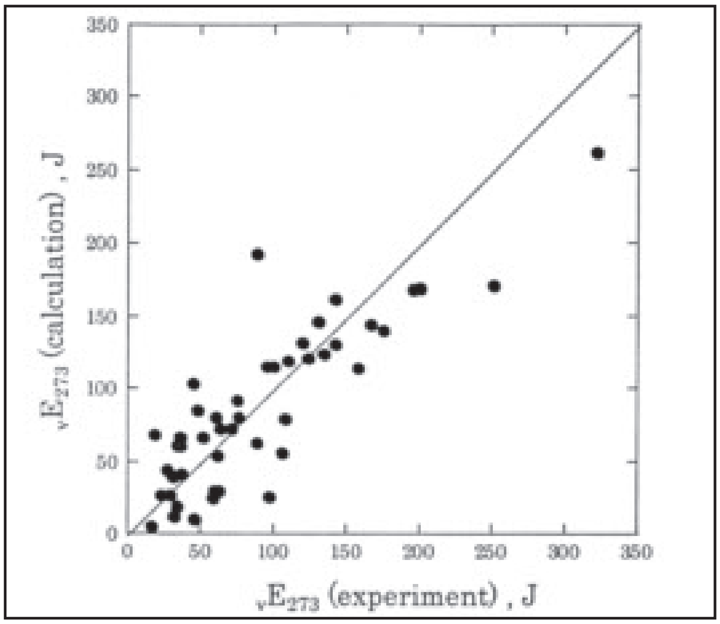

Fig. 3 — The relationship in $_vE_{273}$ between experiment and calculation.

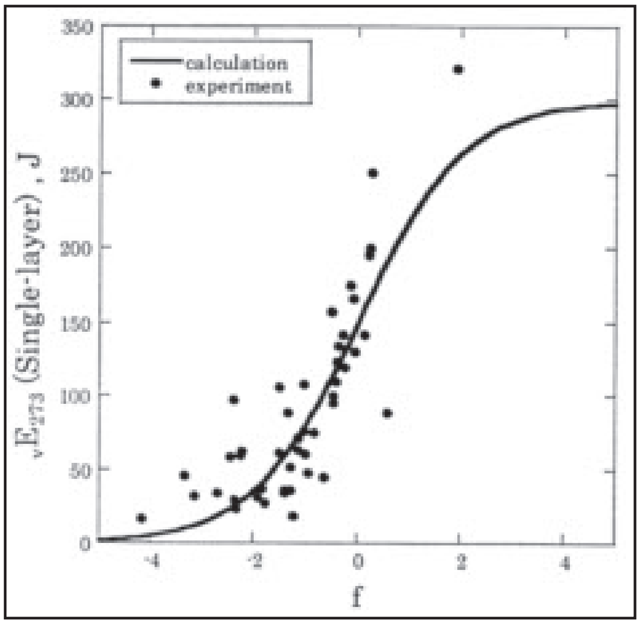

Fig. 4 — Relationship between $_vE_{273}$ (single layer) and f.

It is not clear why the data scatter is limited only in the upper range of the average curve. A reason might be that the match between the notch root and the coarsened microstructure is better for the single-layer weld joint, and besides, it is interpreted as the size effect of the local brittle zone, presented in the Local Approach (Ref. 17). Even if the coarsened microstructure exists on the notch root, as the fraction is low, the HAZ toughness of the multilayer weld joint is more than that of the single-layer weld joint, which appears to be the toughness of all coarsened microstructure.

Derivation of the Conditional Expression to Attain 70 J or 27 J in HAZ Toughness of the Multilayer Weld Joint

Step 3

From the results stated previously, the conditional expression is drawn on to attain 70 J or 27 J in $_vE_{273}$(multilayer). As shown previously, $_vE_{273}$(single layer) is needed to exceed 30 J or 12 J. Calculating from the Expression 1, the condition for f is shown below.

$$f \geq -2.197 \text{ for } {}_vE_{273}(\text{single layer}) \geq 30 \text{ J}, \quad {}_vE_{273}(\text{multilayer}) \geq 70 \text{ J} \qquad (3)$$

$$f \geq -3.178 \text{ for } {}_vE_{273}(\text{single layer}) \geq 12 \text{ J}, \quad {}_vE_{273}(\text{multilayer}) \geq 27 \text{ J} \qquad (4)$$

Then the condition for chemical compositions can be calculated. As was mentioned previously, there is the difference in the reliability for each alloying element. As the coefficient for C, Mn, (P+S), Ti, and N have relatively higher reliability, the formulation is to be done using these six elements. As for the other elements, the average values were

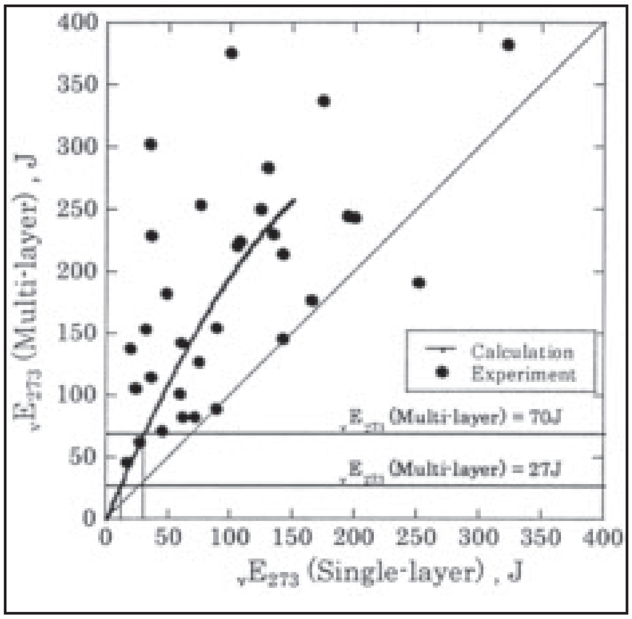

Fig. 5 — Relationship of $_vE_{273}$ between the multilayer and single-layer weld joints.

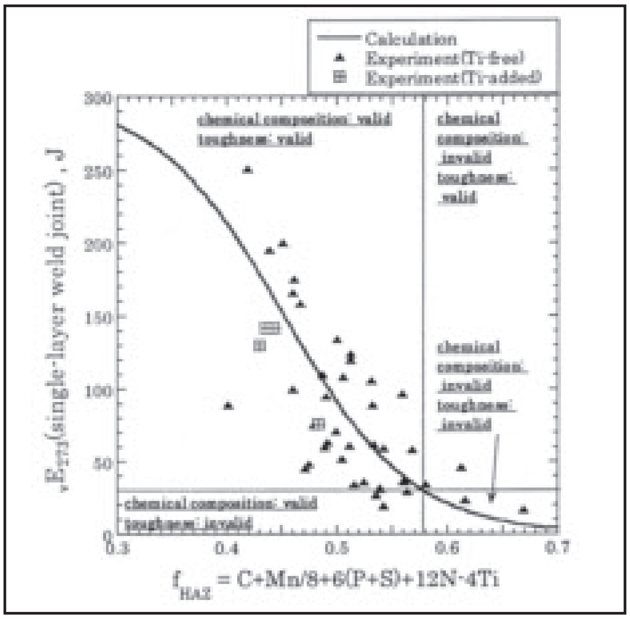

Fig. 6 — Relationship between HAZ toughness of the single-layer weld joints and f_{HAZ}.

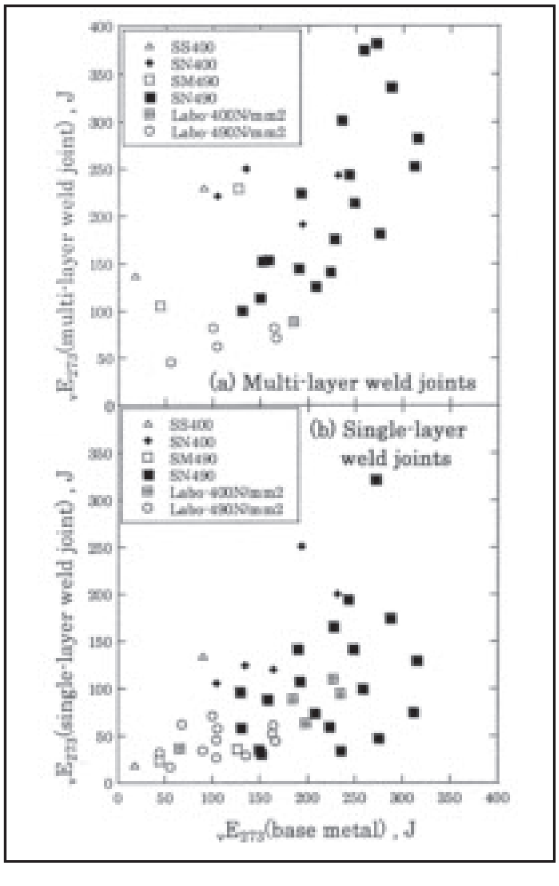

Fig. 7 — The relationship between base metal toughness and HAZ toughness in multilayer and single-layer weld joints.

calculated using all data of the factory-made steels, and it was substituted into the formulation. From this point, the applicable scope of this formulation is limited to SN steel or the equivalent steel. The value is 0.3 mass-% for Si, 0.1 mass-% for (Cu+Ni), 0.06 mass-% for (Cr+Mo+V), and 0.004 mass-% for Nb. Meanwhile, since Ca is often added in SN steel, the average value was also used for the calculation. Substituting the above values into the Expressions 3 and 4, the following expression was derived.

$$-18C - 2Mn - 112(P+S) - 202N + 73Ti \geq -10.17 \text{ for } {}_vE_{273}\text{(single layer)} \geq 30\text{J}, {}_vE_{273}\text{(multilayer)} \geq 70\text{ J} \quad (5)$$

$$-18C - 2Mn - 112(P+S) - 202N + 73Ti \geq -11.15 \text{ for } {}_vE_{273}\text{(single layer)} \geq 12\text{ J}, {}_vE_{273}\text{(multilayer)} \geq 27\text{ J} \quad (6)$$

Simplifying the above expression, the following expression is derived.

$$f_{HAZ} \leq 0.577 \text{ for } {}_vE_{273}\text{(single layer)} \geq 30\text{ J}, {}_vE_{273}\text{(multilayer)} \geq 70\text{ J} \quad (7)$$

$$f_{HAZ} \leq 0.632 \text{ for } {}_vE_{273}\text{(single layer)} \geq 12\text{ J}, {}_vE_{273}\text{(multilayer)} \geq 27\text{ J} \quad (8)$$

$$f_{HAZ} = C + Mn/8 + 6(P + S) + 12N - 4Ti$$

(The content of Ti is treated as 0 when it is lower than 0.005 mass-%.)

In addition, as for Ti, the effect on HAZ toughness is complicated, for example, the interaction with N (Ref. 18). Therefore, attention should be paid when treating it.

Discussion

Verification of the Reliability of the f_{HAZ} Formulation

In this section, the reliability of Formulation 7, the condition to attain 70 J in $_vE_{273}$(multilayer), is verified. The relationship between $_vE_{273}$(single layer) and f_{HAZ} is shown in Fig. 6. The figure is divided into four areas based on the two conditions. One (Condition A) is whether data accommodate to Expression 7, another (Condition B) is whether an experimental value of $_vE_{273}$(single layer) is equal to or more than 30 J. More than 85% of data are in the area of Condition A-valid, Condition B-valid, or Condition A-invalid, Condition B-invalid. As for the data in the area of Condition A-invalid, Condition B-valid, it has no engineering problem because of the safety estimation. As for the problematic area, Condition A-valid, Condition B-invalid, $_vE_{273}$ (single-layer) of two steels in three data are 27 J and 29 J, they are close to 30 J. As a whole,

Table 3 — Result of the Verification of the Chemical Composition Condition

Steel No.	$_{v}E_{273}$ (Multilayer) (J)	$_{v}E_{273}$ (Single Layer) (J)	f_{HAZ}	Verification from the Expression (7)	$_{v}E_{273}$ (Single Layer) ≥30J	$_{v}E_{273}$ (Multilayer) ≥70J
1	221	106	0.5317	O	O	O
2	191	251	0.4191	O	O	O
3	153	31	0.5389	O	O	O
4	376	100	0.4605	O	O	O
5	243	200	0.4514	O	O	O
6	224	108	0.5054	O	O	O
7	230	134	0.4995	O	O	O
8	—	120	0.5118	O	O	O
9	106	23	0.6156	×	×	O
10	229	36	0.5609	O	O	O
11	138	19	0.5428	O	×	O
12	—	158	0.4666	O	O	O
13	250	124	0.5128	O	O	O
14	—	97	0.5588	O	O	O
15	101	59	0.5426	O	O	O
16	115	36	0.5247	O	O	O
17	253	76	0.4838	O	O	O
18	127	75	0.4792	O	O	O
19	302	34	0.5156	O	O	O
20	146	142	0.4355	O	O	O
21	142	60	0.4886	O	O	O
22	214	142	0.4437	O	O	O
23	155	89	0.5319	O	O	O
24	283	130	0.4297	O	O	O
25	182	48	0.4747	O	O	O
26	244	195	0.4389	O	O	O
27	177	166	0.4595	O	O	O
28	337	175	0.4615	O	O	O
29	382	322	0.3444	O	O	O
30	—	63	0.4911	O	O	O
31	89	89	0.4007	O	O	O
32	—	95	0.4900	O	O	O
33	—	37	0.5599	O	O	O
34	—	110	0.4869	O	O	O
35	—	46	0.6121	×	O	O
36	82	71	0.4988	O	O	O
37	—	58	0.5678	O	O	O
38	—	62	0.5329	O	O	O
39	—	32	0.5389	O	O	O
40	71	45	0.4713	O	O	O
41	—	52	0.5046	O	O	O
42	—	29	0.5633	O	×	O
43	62	27	0.5360	O	×	×
44	82	61	0.5109	O	O	O
45	46	17	0.6693	×	×	×
46	—	34	0.5805	×	O	O

the conditional expression to attain $_{v}E_{273}$(single layer) using chemical compositions of steel has adequate reliability for engineering use.

Now, whether $_{v}E_{273}$(multilayer) is equal to or more than 70 J was tested. In Table 3, $_{v}E_{273}$(multilayer), $_{v}E_{273}$(single layer), and f_{HAZ}, and the results based on Expression 7, whether data are equal to or more than 30 J in vE_{273}(single layer), and whether data are equal to or more than 70 J in $_{v}E_{273}$(multilayer) are shown. From this table, the number of samples that are invalid from Expression 7 is two, of which one has $_{v}E_{273}$(multilayer) less than 70 J. Also, among the samples that are judged as "valid" from Expression 7, only Steel No. 43 has 62 J in $_{v}E_{273}$(multilayer). As a whole, 28 of 32 samples adopted the condition 7, and reliability of more than 85% was clarified in this data set.

Advertence on the Utilization of the f_{HAZ} Equation

The aim of this section is to present the necessity, the reliability, and the applicable scope of the f_{HAZ} equation. As was shown in Fig. 2, $_{v}E_{273}$(multilayer) of the most specimens are more than 70 J, especially with all SN steels the toughness was beyond 70 J. From the experimental result, it may be considered that the f_{HAZ} equation is not necessary, but $_{v}E_{273}$(multilayer) can be less than 70 J even when a sample adopts the SN standard, as is shown in steels No. 43 and 45, both of which were laboratory made. Therefore, it is considered that this equation to correlate HAZ toughness with the chemical compositions is needed.

The reliability of Equations 7 and 8 is now discussed. The result of verifying the chemical composition condition is shown in Table 3. The average correlations were adopted in formulating the relationships between $_{v}E_{273}$(single layer) and the chemical compositions, and the correlation of $_{v}E_{273}$(multilayer) and $_{v}E_{273}$(single layer). The condition is not sufficient to attain 70 J or 27 J. The only example is steel No. 43, whose chemical composition complies with Equation 7 but $_{v}E_{273}$(multilayer) was lower than 70 J. If we need the safest equation, the lower bound curve should be needed for both correlations. But the safest equation is excessively conservative, and it contradicts the fact that $_{v}E_{273}$(multilayer) in most SN steels attain 70 J, and it is considered to lose the engineering availability. Then, as an indicator to attain 27 J or 70 J in $_{v}E_{273}$(multilayer), the f_{HAZ} equation is proposed.

The applicable scope of f_{HAZ} is also important. Equations 7 and 8 are based on the data of the welding condition where heat input is 4 kJ/mm and preheating and interpass heating temperature are 623 K. They are not available if the welding condition is much different. Attention should be paid especially to low heat input and single-layer welding such as tack welding. For example, in the case of 2 kJ/mm in heat input and the single-layer weld, the microstructure is mainly composed of high-hardness martensite, and therefore, the toughness is generally low. Since the mechanism of the deterioration in HAZ toughness is different from the case with this study, the equation presented cannot be used.

Also, care should be taken as to the effect of the plate thickness. Even with the same welding conditions, as the cooling rate can change depending on the plate thickness, it can affect HAZ toughness. The thinner the plate thickness, the lower the cooling rate is. So, decreasing the plate thickness may deteriorate HAZ toughness in the same welding conditions. However, the range of plate thickness is 15 to 40 mm, and more than 60% of the samples are 22 to 28 mm in thickness. This subtle change in plate thickness can establish the accuracy of Equations 7 and 8.

Notice should be taken of the chemical

compositions. If the content of a composition exceeds the level of the steels used, there is a possibility for HAZ toughness to deteriorate more than expected. Especially, if other elements than C, Mn, P, S, N, and Ti used in the fHAZ equation, were used for the regression as the average value of steel used, the fHAZ formulation cannot be applied to steel containing a different content to a large degree.

Titanium is the one element that improves HAZ toughness with an increase in content. In contrast, if the content exceeds 0.013%, which is the maximum value of steels used, or the ratio of Ti content to the content of N changes remarkably, there is a possibility to deteriorate HAZ toughness. On the other hand, since the small amount of Ti may have less effect on toughness improvement, the lower limitation should be given. In this study, the detail is not examined, but for example, it is suggested the minimum value as 0.005 mass-% Ti.

Effect of the Base Metal Toughness

The relationships between the base metal toughness and HAZ toughness in multilayer weld joints and single-layer weld joints is shown in Fig. 7. Both figures have a positive correlation. In the region of HAZ1, where HAZ toughness was evaluated, the microstructure of the base metal does not remain because of the heating above A_{c3}. The reason for the positive correlations may be attributed to the increase of elements such as C, P, S, and N leads to base metal toughness deterioration, as well as that of HAZ toughness. It means that the positive correlations of toughness between the base metal and HAZ are indirectly related to chemical compositions.

Conclusions

The HAZ toughness in beam-to-column connections of structural steel (SN steel) and its chemical compositions were investigated. The following results were derived:

1) In the multilayer weld joints, ${}_{v}E_{273}$ (absorbed energy at 273 K by the Charpy impact test) was more than 27 J but partly less than 70 J.

2) In the single-layer weld joints, ${}_{v}E_{273}$ was usually less than those in the multilayer weld joints, and sometimes it was less than 27 J.

3) A chemical composition parameter to attain a certain level of HAZ toughness value was proposed. When JIS G 3136 SN steel or the equivalent steel is used, and a multilayer weld joint is made with a heat input of 4 kJ/mm and preheating or interpass heating temperature at 673 K, an approximate condition to attain 70 J or 27 J in the Charpy impact energy at 273 K is given below.

$$f_{HAZ} \leq 0.577 \text{ for } {}_{v}E_{273}\text{(single layer)} \geq 30\text{ J}, {}_{v}E_{273}\text{(multilayer)} \geq 70\text{ J}$$

$$f_{HAZ} \leq 0.632 \text{ for } {}_{v}E_{273}\text{(single-layer)} \geq 12\text{ J}, {}_{v}E_{273}\text{(multilayer)} \geq 27\text{ J}$$

$$f_{HAZ} = C + Mn/8 + 6(P + S) + 12N - 4Ti$$

(Note: The content of Ti should be considered as 0 when it is equal or less than 0.005 mass-%.)

4) From the experimental data, it was clarified that the proposed expression has 85% reliability.

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