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Determination of Necessary Preheating Temperature in Steel Welding

Findings include a new carbon equivalent to assess the susceptibility of steel to cold cracking more satisfactorily

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ABSTRACT. Various tests used when determining critical preheating temperatures to avoid cold cracking were examined. These included the Stout slot weld, H-slit type, V-groove restraint, and y-groove restraint tests. Both conventional and newly developed types of steel having carbon contents ranging between 0.02 and 0.26% were used.

Examination of the cracking tests resulted in the proposing of a new carbon equivalent that more satisfactorily assesses the susceptibility of steel to cold cracking than do CE(IIW) and P_{cm}. It is expressed as:

$$CE = C + A(C) \cdot \left\{ \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr + Mo + Nb + V}{5} + 5B \right\}$$

where $A(C) = 0.75 + 0.25 \tanh \{20 (C - 0.12)\}$.

As a parameter describing the probability of the occurrence of cold cracking in steel welding, a cracking index (CI) was proposed. It is expressed as:

$$CI = CE + 0.15 \log H_{JIS} + 0.30 \log(0.017 K_t \sigma_w)$$

According to the procedure proposed in this study, the necessary preheating temperatures to avoid cold cracking are determined by satisfying the following criterion:

$$t_{100} \geq (t_{100})_{cr}$$

where t_{100} is the cooling time to 100°C (212°F); this is influenced, not only by the preheating temperature employed, but also by welding heat input, plate thickness and preheating method. Critical time $(t_{100})_{cr}$ is given as:

$$(t_{100})_{cr} = \exp (67.6\, CI^3 - 182.0\, CI^2 + 163.8\, CI - 41.0)$$

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Introduction

Methods to determine the necessary preheating temperature for the prevention of cold cracking in steel welding include the 1974 British Standard 5135 (Ref. 1) and a procedure described in *Japan Steel Structure Construction* (JSSC – Ref. 2). However, there is a considerable difference between the necessary preheating temperatures determined by the two procedures.

British Standard 5135 uses the IIW carbon equivalent as a parameter for determining the preheating temperature, while the JSSC procedure uses Ito's carbon equivalent, P_{cm} (Ref. 3). The IIW carbon equivalent satisfactorily evaluates the cold cracking susceptibility of ordinary carbon or carbon-manganese steels; however, the low-carbon low-alloy steels, such as the recently developed pipeline steels, are more accurately assessed by P_{cm}. This has been a problem, especially in deciding the allowable value for the chemical composition of pearlite-reduced pipeline steels or low-carbon low-alloy structural steels.

Experimental Procedure

Weld Cracking Tests

Stout, *et al.* (Ref. 4) proposed a slot-weld cracking test in which the weldability of pipeline steel, in the case of welding with high-hydrogen types of cellulose electrodes, can easily be evaluated. Figure 1 shows the dimensions of the standard test piece used.

It was noticed that fluctuations in width of the root opening of this test piece greatly influenced experimental results (Ref. 5). Therefore, slots with a 2.4 mm (0.09 in.) opening were machined on the flat plates. The accuracy of the machined openings was within 0.1 mm (0.004 in.). The weld metal was deposited on the slot using flat position welding with a 4 mm (0.16 in.) diameter electrode cellulosic-type AWS E7010 in a cold chamber where the ambient temperature was held at 10°C (50°F). The welding voltage, current and torch speed were approximately 28V, 160A, and 5 mm/s (11.8 ipm), respectively.

In order to investigate cold cracking in the case of low-hydrogen welding, the present study used the results of H-slit tests (Ref. 6, 7), V-groove tests and y-groove tests (Ref. 8). Figure 2 shows the shape of the H-slit test piece in which the restraint intensity is varied with a change in the slit length B_s. The restraint intensity R_F (kgf/mm · mm) is a force per unit weld length necessary to reduce a root opening by unit length. Table 1 shows R_F for each test piece used in the present study. The meaning of r_f and R_F is explained in the Appendix under the heading, "Restraint Stress Acting on Weld."

In each type of cracking test, test pieces were preheated to the various temperatures up to 200°C (392°F) until crack initiation was completely stopped. The Stout test pieces were preheated in the furnace, while other test pieces were locally preheated by electrical strip heaters in the manner shown in Fig. 2. In the case of multipass welding, the interpass temperatures were kept almost the same

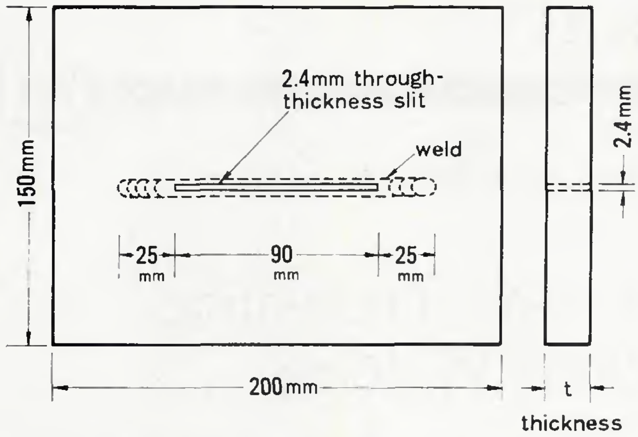
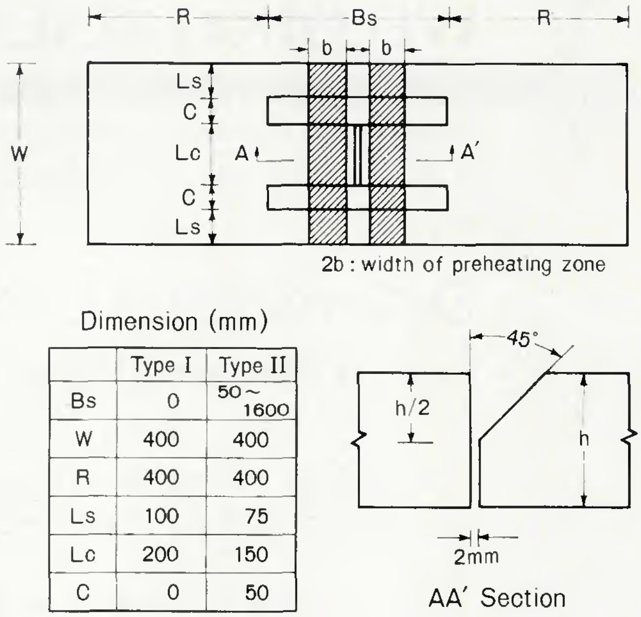


Fig. 1—Shape of Stout slot-weld test piece



	Type I	Type II
Bs	0	50 ~ 1600
W	400	400
R	400	400
Ls	100	75
Lc	200	150
C	0	50

Fig. 2 (right)—Shape of H-slit restraint cracking test piece

as the preheating temperatures.

Each test piece was transversely cut into five sections after more than 72 hours (h) had passed since completion of the welding. Macrographic observation of nital-etched weld sections led to the determination of the critical preheating temperatures T_o^* at which the occurrence of cold cracks was prevented. Figure 3 shows an example of a weld with a root crack in the Stout test.

Materials

The Stout slot weld tests were carried out with various types of steels employed for ordinary structures, pressure vessels, boilers, and pipelines. Their tensile strengths ranged between 40 and 85 kgf/mm^2 (57 and 121 ksi), and their chemical compositions are shown in Table 2. In the Stout test, one type of electrode, i.e., AWS E7010, was used irrespective of the strength level of the tested steel. The hydrogen content in the deposited weld metal using this electrode was 35 ml/100g by JIS glycerin displacement method. This value, H_{JIS}, can be converted to H_{IIW} by the mercury displacement method as (Ref. 9):

$$H_{IIW} = 1.30\,H_{JIS} + 0.61 \qquad (1)$$

Table 3 shows the chemical compositions of steels used in the H-slit cracking tests, the V-groove tests and the y-groove restraint tests. These steels were for structural or pressure vessel usage with greater thicknesses up to 100 mm (3.9 in.). Tests, other than the Stout test, employed electrodes whose strength corresponded to those of the steels tested. Table 4 shows nominal yield strengths and hydrogen contents of the welding materials used; welding conditions for the cracking tests are also described in Table 4.

Results and Discussion

Critical Preheating Temperature Measured in Tests

Critical preheating temperature T_o^* in the Stout tests is shown in Table 2. The results of the H-slit, V-groove and y-groove restraint tests are summarized in Table 5. K_t in Table 5 is the stress concentration factor at the notch where a crack is initiated, and its value is given in the Appendix under the heading, "Restraint Stress Acting on Weld." The mean stress acting on the weld metal is given as a function of σ_y and R_F as (Ref. 10):

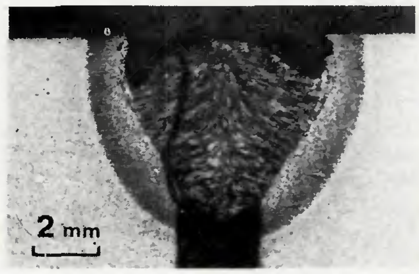


Fig. 3—Root crack in Stout's slot test

$$\left.\begin{aligned} \sigma_w &= 0.050\,R_F, \ (R_F \leq 20\,\sigma_y) \\ \sigma_w &= \sigma_y + 0.0025\,(R_F - 20\,\sigma_y), \\ &\quad (R_F > 20\,\sigma_y) \end{aligned}\right\} \qquad (2)$$

The critical preheating temperatures were obtained separately for single-pass root cracking (Fig. 4), multipass root cracking (Fig. 5) and multipass toe cracking (Fig. 6) for each steel tested. Toe cracks were not observed in the specimens of SM41B, SM53B, HW45, and HW70 steel. T_o^* for multi-pass root cracking was found to be less than that for single-pass root cracking by over 50°C (122°F). Table 5 also lists t_{100}, which is the duration of the cooling time to 100°C (212°F) after welding and corresponds to T_o^* measured in the tests.

The weldment eventually cools to the ambient temperature whether it is preheated or not. Some hydrogen escapes from the weld metal surface during the cooling period after welding. However, hydrogen escape becomes more and more inactive with a decrease in the temperature of the weld metal and it becomes negligibly small at temperatures less than 100°C (212°F).

The residual hydrogen in welds contributes to the initiation of cold cracking when it cools below 100°C (212°F) in an

Table 1—Restraint Intensity of H-Slit Test Piece(a)

Slit length B_s, mm	2-D restraint coefficient, r_f $kgf/mm^2 \cdot mm$	Plate thickness h, mm	Restraint intensity R_F, $kgf/mm \cdot mm$
0	69.0	38	2765
0	69.0	50	3374
0	69.0	75	4265
0	69.0	100	4784
300	20.0	50	998
1600	5.9	50	290

(a) Conversion factors: pound force/in.^{3} = 375.7 × $kgf/mm^2 \cdot mm$; in. = 25.4 × mm; ksi = 1.422 × $kgf/mm \cdot mm$.

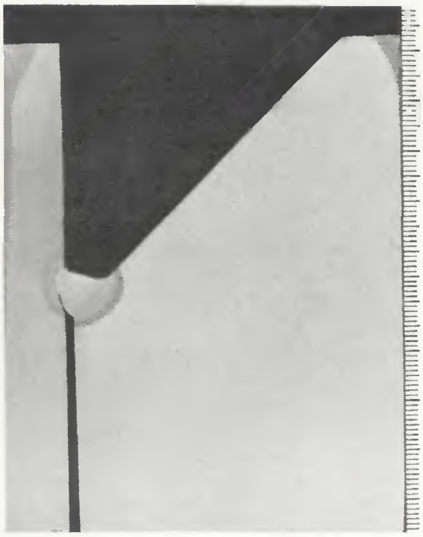


Fig. 4 — Single-pass root crack in H-slit test

ordinary structural steel weld. It follows that the t_{100} is significant in selecting preheating temperatures.

Preheating increases the cooling time to 100°C (212°F) and thus is effective in preventing the initiation of cold cracking. However, the duration of the cooling time to 100°C (212°F) is determined, not only by the preheating temperature, but also by the plate thickness, the particular preheating method used and other factors. These relations are shown in Figs. 11 and 12 in the Appendix. Consequently, it is advisable to consider the critical cooling time to 100°C (212°F) rather than rely solely on the preheating temperature when desiring to avoid cold cracking in steel welding (Ref. 2).

Carbon Equivalent to Assess Cold Cracking

Many carbon equivalents have been proposed as parameters indicating a steel's susceptibility to cold cracking at the heat-affected zone. They can be divided into two groups wherein CE(IIW) is of the first group, and Ito's carbon equivalent, P_{cm} (Ref. 3), belongs to the second. They are expressed as:

$$CE(IIW) = C + \frac{Mn}{6} + \frac{Cu + Ni}{15} + \frac{Cr + Mo + V}{5} \quad (3)$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (4)$$

P_{cm} has been shown to be reliable for evaluating the cold cracking tendency in low-carbon low-alloy steel (Ref. 11). On the other hand, CE(IIW) is reported to be a more appropriate parameter than P_{cm} for evaluating the cold cracking susceptibility of steels whose carbon content is more than 0.16% (Ref. 7). Therefore, it is not possible for one simple carbon equivalent formula to describe, overall, the cold cracking tendency of steels if their

Table 2—Chemical Compositions (%) and Critical Preheating Temperatures of Steels in Stout Slot Weld Tests[a]

Symbol	Steel	Thickness, mm	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb	Ti	B	CE (IIW)	P_{cm}	$CE_{eq\,(5)}$	T_o,* °C
A	JIS SM53	20	.160	.40	1.41	.020	.008	.01	.01	.01	–	.059	.038	–	–	.410	.251	.411	75
B	JIS SM53B	20	.159	.37	1.40	.018	.012	.01	.02	.01	–	.026	–	–	–	.401	.245	.395	75
C	JIS SM50C	20	.149	.25	1.33	.019	.005	.01	.01	.01	–	–	.026	–	–	.374	.225	.361	50
D	BS4360 50D	20	.173	.45	1.48	.021	.006	–	.01	.01	–	.056	.046	–	–	.434	.268	.446	100
E	ASTM A516 Gr. 70	20	.231	.27	1.19	0.19	.007	.02	.03	.03	–	.036	–	–	.0005	.446	.309	.458	150
F	ASTM A537 C1.2	20	.142	.41	1.44	.025	.003	–	.20	.02	–	.016	–	–	.0002	.403	.236	.377	125
G	ASTM A633C	20	.099	.35	1.46	.013	.004	.15	.17	.02	–	.040	.039	–	.0006	.376	.202	.294	75
H	ASTM A299	20	.254	.27	1.37	.016	.005	.14	.16	.15	.14	–	–	–	.0002	.560	.358	.569	≥200
I	JIS SB49	20	.240	.29	.87	.019	.005	–	.13	.12	–	–	–	–	.0003	.418	.301	.428	100
J	WES HW45	20	.141	.30	1.33	.020	.006	.01	–	.01	–	.055	–	–	.0002	.376	.224	.352	75
K	WES HW45	20	.065	.28	1.38	.013	.003	.03	–	.21	.21	.038	–	–	.0015	.389	.181	.254	≤10
L	WES HW70	20	.130	.29	.88	.010	.005	.22	.81	.54	.47	.044	–	–	.0018	.556	.280	.477	150
M	WES HW70	20	.112	.24	.87	.019	.006	.23	.02	.85	.33	.046	–	–	.0005	.519	.247	.410	100
N	JIS STK41	12.7	.230	.04	.68	.014	.012	.01	.01	.02	–	–	–	–	–	.349	.267	.350	≤50
O	API X60	20	.091	.29	1.32	.017	.003	.01	.01	.01	.09	–	.040	–	–	.331	.176	.253	50
P	API X65	14	.240	.35	1.39	.015	.012	.01	.01	.02	–	–	–	–	–	.477	.323	.491	≤125
Q	API X65	20	.049	.29	1.56	.017	.005	–	.27	.01	.25	.068	.049	.007	.0002	.393	.166	.240	≤10
R	API X70	16	.021	.14	1.59	.018	.003	–	–	–	–	–	.041	.017	.0010	.286	.110	.166	≤10
S	API X70	20	.020	.13	1.89	.020	.002	–	–	–	–	–	.048	.016	.0010	.335	.124	.191	≤10
T	API X80	20	.018	.16	2.01	.019	.003	–	.32	–	.30	–	.052	.018	.0010	.434	.154	.239	≤10

(a) Conversions: in. = 25.4 × mm; °F = (1.8 × °C) + 32.

Table 3—Chemical Compositions of Steels Used in Restraint Cracking Tests, %

Steel	Thickness, mm[a]	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb	B	CE (IIW)	$CE_{eq\,(5)}$
JIS SM41B	38	.17	.24	.73	.025	.008	–	–	–	–	–	–	–	.0292	0.294
JIS SM41B	100	.13	.26	.97	.017	.010	–	–	–	–	–	–	–	0.292	0.268
JIS SM53B	50	.17	.36	1.50	.017	.011	–	–	–	–	.06	–	–	0.432	0.430
WES HW45	32	.13	.25	1.36	.023	.006	–	–	.01	–	.05	–	–	0.369	0.329
WES HW45	38	.14	.32	1.18	.011	.005	–	–	.19	–	.05	–	–	0.385	0.358
WES HW45	50	.14	.43	1.08	.020	.004	–	–	.13	.11	.05	–	–	0.378	0.356
WES HW70	50	.11	.24	.82	.006	.001	.22	1.04	.47	.40	.04	–	.001	0.513	0.390
WES PMS25	75	.17	.48	1.56	.013	.004	.09	–	–	.15	–	–	–	0.466	0.467
WES PMS35	75	.18	.46	1.54	.015	.003	.09	.30	–	.23	.04	–	–	0.517	0.516
ASTM A516 Gr.70	100	.22	.25	1.14	.018	.007	–	–	–	–	.03	–	–	0.416	0.425
JIS SB49M	100	.24	.28	.85	.026	.005	–	.24	.18	.10	–	–	.001	0.454	0.465
JIS SB56M	100	.16	.25	1.27	.012	.008	.14	.35	.49	.46	–	–	–	0.594	0.562

(a) in. = 25.4 × mm.

Table 4—Welding Materials and Conditions for Restraint Cracking Tests[(a)]

Electrode	Diameter, mm	Nominal yield strength, kgf/mm²	H_{JIS} ml/100g	Current, A	Voltage, V	Speed, mm/min	Heat input, J/mm	Cracking test
AWS E7010	3.2	50	31.8	130	25	290	672	V-groove test
AWS E7010	4.0	50	35.0	160	30	300	960	Stout test
JIS D4301	5.0	40	32.8	220	28	123	3000	H-slit test
JIS D4316	5.0	40	3.7	230	25	115	3000	H-slit test
JIS D5016	5.0	50	3.4	230	25	115	3000	H-slit test
JIS D5816	4.0	60	0.4 ~ 5.0	170	25	150	1700	y-groove test
JIS D5816	5.0	60	0.4 ~ 5.7	230	25	115	3000	H-slit test
JIS D8016	5.0	80	2.0	230	25	115	3000	H-slit test

(a) Conversions: in. = 25.4 × mm; ksi = 1.422 × kgf/mm².

carbon contents range widely.

It is with this point of view in mind that the authors propose the following carbon equivalent, which has an accommodation factor A(C) as a function of the carbon content:

$$CE = C + A(C) \cdot \left\{ \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr + Mo + Nb + V}{5} + 5B \right\} \quad (5)$$

where $A(C) = 0.75 + 0.25 \tanh \{20(C - 0.12)\}$. (6)

A(C) increases with an increase in carbon content. It approaches 0.5 as the carbon content decreases below 0.08% and 1.0 as it increases above 0.18%. The relationship between this carbon equivalent and CE(IIW) is shown in the Appendix under "New Carbon Equivalent."

Experimental results from the Stout cracking tests were used to compare the three types of carbon equivalents for validity in assessing the cold cracking tendency of steels. The relation of T_o* to the three carbon equivalents was plotted in Fig. 7. It is seen that the carbon equivalent expressed in equation (5) had the highest linear correlation coefficient (r = 91.1%); therefore, it is the most reliable of the three carbon equivalents, provided that the carbon content of the steels to be compared ranges widely.

Index to Describe Cracking Probability

Ito, *et al.* proposed P_w (Ref. 3) and Suzuki recently proposed P_H (Ref. 11) as parameters to describe the likelihood of cold cracking. The parameters involve chemical composition, hydrogen content and acting stress, which are three major causes of cold cracking in welds.

Table 5—Results of Restraint Cracking Tests and Estimated Critical Preheating Temperatures

Steel	h, mm	$CE_{eq(5)}$	H_{JIS}, ml/100g	σ_y, kgf/mm₂	K_t, (groove)	R_F, kgf/mm²	σ_w, kgf/mm²	CI	2b (mm)	E_J, (kJ/mm)	Crack[(a)]	Observed T_o* (°C)	Observed $(t_{100})_{Cr}$ s	Estimated T_o*, (°C)	Estimated $(t_{100})_{Cr}$ s	Ref.
SM41B	38	.294	3.7	40	8(ν)	2765	44.9	.615	100	3.0	S.R.	50	200	90	736	6
SM41B	38	.294	32.8	40	8(ν)	2765	44.9	.757	100	3.0	S.R.	125	1200	250	2930	6
SM53B	50	.430	3.4	50	8(ν)	290	14.5	.598	100	3.0	S.R.	75	390	80	546	6
SM53B	50	.430	3.4	50	8(ν)	3374	55.9	.774	100	3.0	S.R.	≥200	≥2100	250	3127	6
SM53B	50	.430	3.4	50	8(ν)	3374	55.9	—	100	3.0	M.R.	100	—	—	—	6
SM53B	50	.430	3.4	50	8(ν)	3374	55.9	.774	200	3.0	S.R.	175	2300	200	3127	6
HW45	50	.356	0.4	60	8(ν)	3374	65.4	.581	100	3.0	S.R.	50	200	70	391	6
HW45	50	.356	1.3	60	8(ν)	3374	65.4	.658	100	3.0	S.R.	125	1200	130	1354	6
HW45	50	.356	5.7	60	8(ν)	3374	65.4	.754	100	3.0	S.R.	200	2100	240	2892	6
HW45	38	.358	.04	60	4(y)	2765	63.9	.490	100	1.7	S.R.	≤25	≤60	≤0	33	8
HW45	38	.358	2.2	60	4(y)	2765	63.9	.601	100	1.7	S.R.	100	550	100	577	8
HW45	38	.358	5.0	60	4(y)	2765	63.9	.654	100	1.7	S.R.	150	1600	130	1290	8
HW45	32	329	3.2	60	1.5(V)	1500	60.8	.462	200	1.0	S.R.	≤25	≤30	≤0	12	8
HW45	32	329	31.8	50	1.5(V)	1500	58.2	.611	200	1.0	S.R.	50	90	125	688	8
HW70	50	.390	2.0	80	8(ν)	3374	84.4	.753	100	3.0	S.R.	≥200	≥2100	240	2880	6
HW70	50	.390	2.0	80	8(ν)	3374	84.4	—	100	3.0	M.R.	100	—	—	—	6
HW70	50	.390	2.0	80	8(ν)	998	49.9	.685	100	3.0	S.R.	175	1900	175	1807	6
HW70	50	.390	2.0	80	8(ν)	290	14.5	.523	100	3.0	S.R.	50	200	≤0	94	6
PMS25	75	.467	3.4	50	8(ν)	4265	58.1	.816	200	3.0	S.R.	200	3000	220	3464	7
PMS25	75	.467	3.4	50	8(ν)	4265	58.1	—	200	3.0	M.R.	125	—	—	—	7
PMS25	75	.467	3.4	50	1.5(toe)	4265	58.1	.598	200	3.0	M.T.	100	700	90	546	7
PMS35	75	.516	2.0	60	8(ν)	4265	67.7	.850	200	3.0	S.R.	225	3600	225	3599	7
PMS35	75	.516	2.0	60	8(ν)	4265	67.7	—	200	3.0	M.R.	150	—	—	—	7
PMS35	75	.516	2.0	60	1.5(toe)	4265	67.7	.632	200	3.0	M.T.	125	1300	110	960	7
SM41B	100	.268	3.4	40	8(ν)	4784	50.0	.597	200	3.0	S.R.	50	150	90	536	7
SM41B	100	.268	3.4	40	8(ν)	4784	50.0	—	200	3.0	M.R.	≤25	—	—	—	7
SM41B	100	.268	3.4	40	1.5(toe)	4784	50.0	.379	200	3.0	M.T.	≤25	≤90	≤0	1	7
A516 Gr.70	100	.425	3.4	50	8(ν)	4784	59.5	.777	200	3.0	S.R.	175	2900	175	3160	7
A516 Gr.70	100	.425	3.4	50	8(ν)	4784	59.5	—	200	3.0	M.R.	125	—	—	—	7
A516 Gr.70	100	.425	3.4	50	1.5(toe)	4784	59.5	.559	200	3.0	M.T.	≤50	≤150	80	240	7
SB49M	100	.465	3.4	50	8(ν)	4784	59.5	.817	200	3.0	S.R.	200	3400	200	3470	7
SB49M	100	.465	3.4	50	8(ν)	4784	59.5	—	200	3.0	M.R.	150	—	—	—	7
SB49M	100	.465	3.4	50	1.5(toe)	4784	59.5	.599	200	3.0	M.T.	≤75	≤300	90	556	7
SB56M	100	.562	1.9	60	8(ν)	4784	69.0	.895	200	3.0	S.R.	225	4000	200	3664	7
SB56M	100	.562	1.9	60	8(ν)	4784	69.0	—	200	3.0	M.R.	150	—	—	—	7
SB56M	100	.562	1.9	60	1.5(toe)	4784	69.0	.677	200	3.0	M.T.	150	2000	140	1671	7

(a) Type of crack: S.R. — single pass root crack; M.R. — multipass root crack; M.T. — multipass toe crack

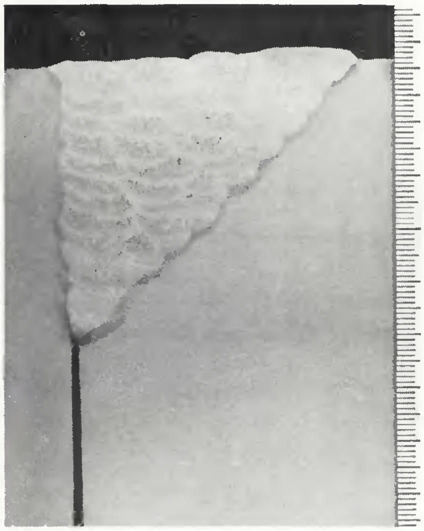


Fig. 5—Multipass root crack in H-slit test

In this study, a cracking index, based on the same concept as P_w or P_H, was introduced using the new carbon equivalent (CE) from equation (5) as:

$$CI = CE + 0.15 \log H_{JIS} + 0.30 \log(0.017\ K_t\ \sigma_w) \quad (7)$$

A CI was computed for each of the weld cracking tests and is also listed in Table 5. The CI thus obtained were plotted against $(t_{100})_{cr}$ corresponding to the T_o* in Fig. 8 by making use of $t_{100} - T_o$ relations shown in Figs. 11 and 12 in the Appendix. Then, a curve representing the relationship between $(t_{100})_{cr}$ and CI was obtained by best fitting it to the plotted experimental results in Fig. 8. It was expressed as:

$$(t_{100})_{cr} = \exp(67.6\ CI^3 - 182.0\ CI^2 + 163.8\ CI - 41.0) \quad (8)$$

The $(t_{100})_{cr}$ is the critical value, in that cracking can be prevented under the welding condition described by the cracking index, CI, if the duration of the cooling to 100°C (212°F) in actual welding exceeds the $(t_{100})_{cr}$.

Determination of Necessary Preheating Temperature

The following procedure may be used to determine the necessary preheating temperature in steel welding. It is the same in its basic concept as the procedure proposed by JSSC (Ref. 2).

1. Obtain the carbon equivalent of the steel to be welded using equation (5).
2. Obtain the hydrogen content of the welding material.
3. Determine K_t using the chart in Fig. 9, and σ_w using Fig. 10 and equation (2).
4. Calculate CI using the values of CE from equation (5), H_{JIS}, K_t and σ_w using equation (7).
5. Calculate $(t_{100})_{cr}$ from CI using equation (8).
6. Finally, select the preheating temperature, taking into account h, 2b, and E_j in Figs. 11 and 12 so that the following condition is satisfied:

$$t_{100} > (t_{100})_{cr} \quad (9)$$

The necessary preheating temperatures were estimated according to the procedure for H-slit tests and others. They are shown as the estimated T_o* in Table 5. Since the procedure above was entirely based on the weld cracking tests

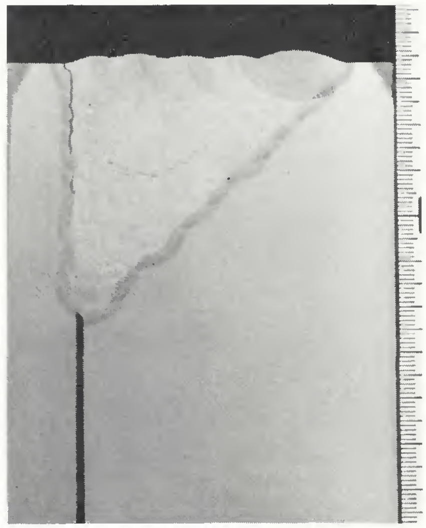


Fig. 6—Multipass toe crack in H-slit test

conducted by the authors, it may have some limitations. Moreover, the following precautions are required:

1. Unnecessary high preheating temperatures are given for the welding of mild steels and for the welding with high-hydrogen welding materials. Both cases did not fit equation (8) as seen in Fig. 8.
2. Weld metal cracking is more likely to occur than heat-affected zone cracking when welding steels with a lower CE or when using high-hydrogen materials.
3. The critical preheating temperature for multipass root cracking is less than that for single-pass root cracking by approximately 50°C (90°F), provided that interpass temperatures are kept

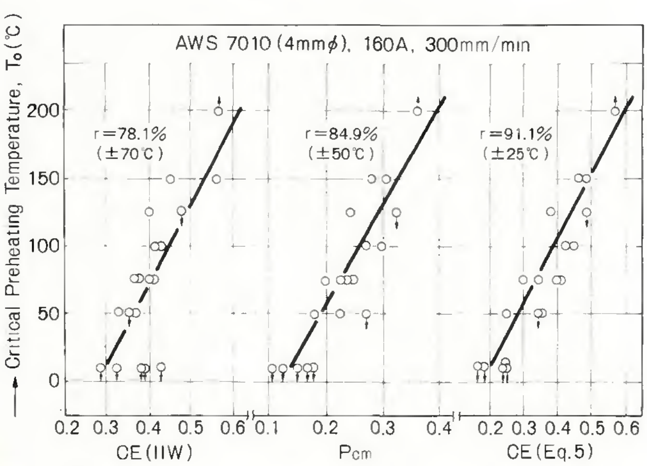


Fig. 7—Linear correlation between Stout slow-weld test results and carbon equivalents

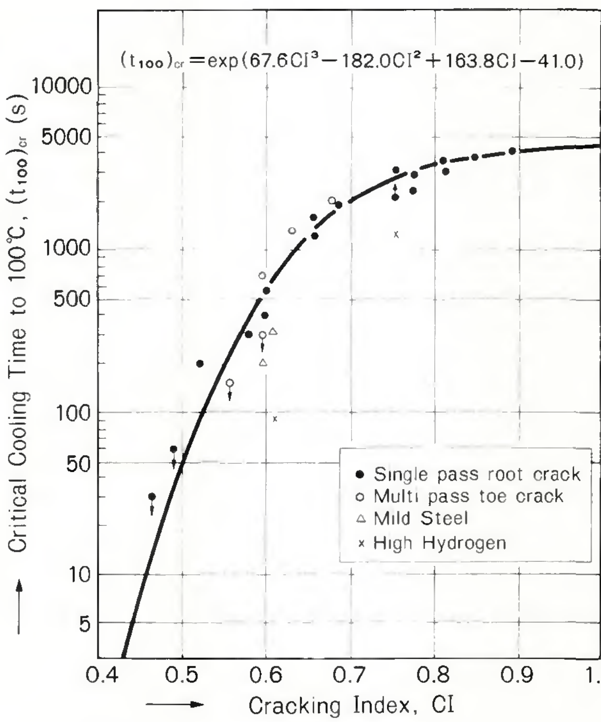


Fig. 8 (right)—Relationship between critical cooling time to 100°C and cracking index (CI)

Groove type	K_t
y (root)	4
Double-Vee (root)	3.5
Y (root)	4 ~ 5
Single-bevel (root)	6 ~ 8
V (root)	1.5
y, x, Y, V, U (toe)	1.5

Fig. 9 — Stress concentration factors at root and toe weld positions

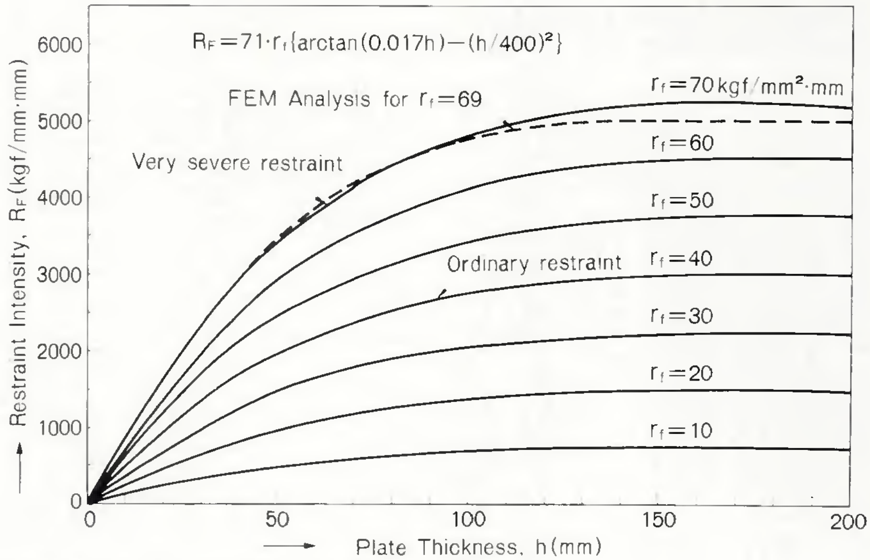


Fig. 10 — Relation of restraint intensity to plate thickness

higher than the preheating temperatures.

4. If root cracks are to be removed by backgouging, the preheating temperature for toe cracking (K_t = 1.5) may be employed.

Conclusions

1. The CE from equation (5) is a more appropriate parameter than CE(IIW) or P_{cm} for assessing the susceptibility of steel to cold cracking.

2. The cracking index, CI, given by equation (7) satisfactorily describes the likelihood of cold cracking of steel under varying chemical compositions, welding material hydrogen content, and joint restraint intensity.

3. The necessary preheating temperature can be determined by satisfying the condition that $t_{100} > (t_{100})_{cr}$. The critical cooling time $(t_{100})_{cr}$ is given as a function of CI by equation (8).

Appendix

Restraint Stress Acting on Weld

The occurrence of cracking is greatly influenced by the severity of the notch where a crack is initiated. Figure 9 shows the stress concentration factors at weld roots and toes with various types of weld grooves (Ref. 11).

Watanabe, *et al.* (Ref. 12) calculated the two-dimensional restraint coefficient, r_f, for an H-slit test specimen as:

$$r_f = E/\{B_s + (L_c/2L_s)B_s + B_s'\} \quad (A1)$$

where E is Young's modulus; B_s, L_c and L_s

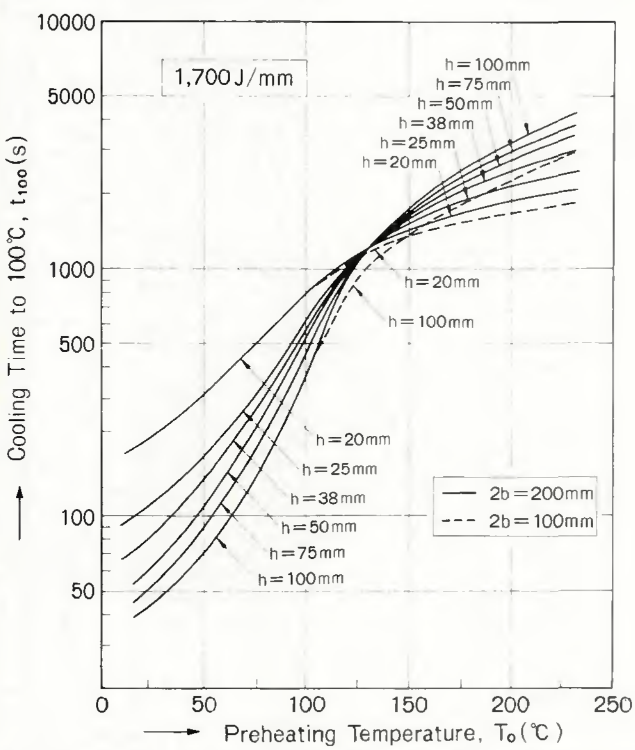


Fig. 11 — Relation between cooling time to 100°C and preheating temperature (E_j = 1,700 J/mm)

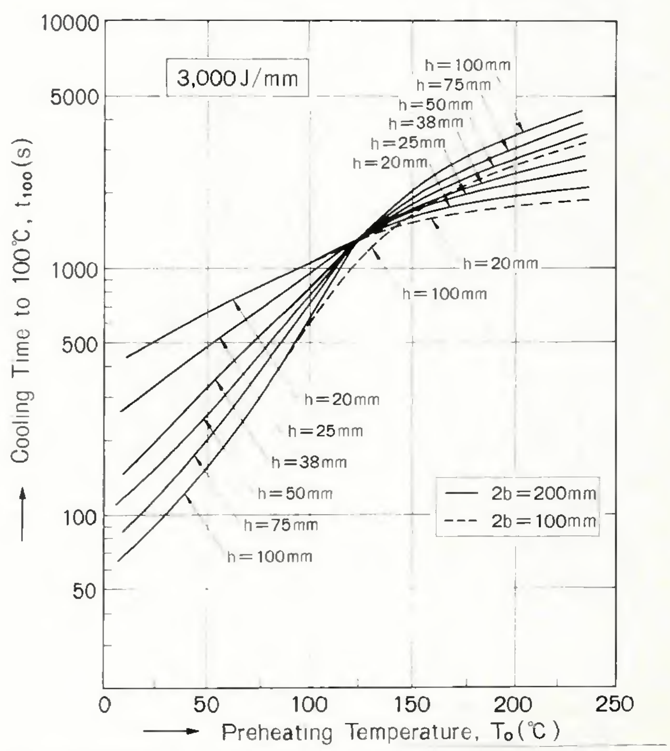


Fig. 12 — Relation between cooling time to 100°C and preheating temperature (E_j = 3,000 J/mm)

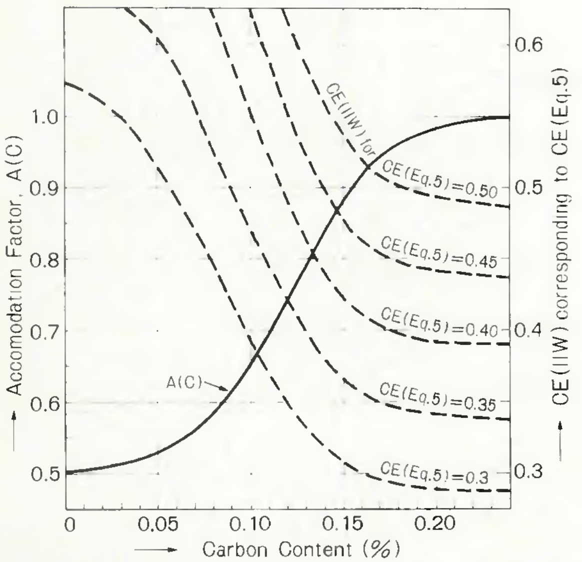


Fig. 13—Carbon content dependence of accommodation factor, A(C), and CE(IIW) value equal to $CE_{eq(5)}$

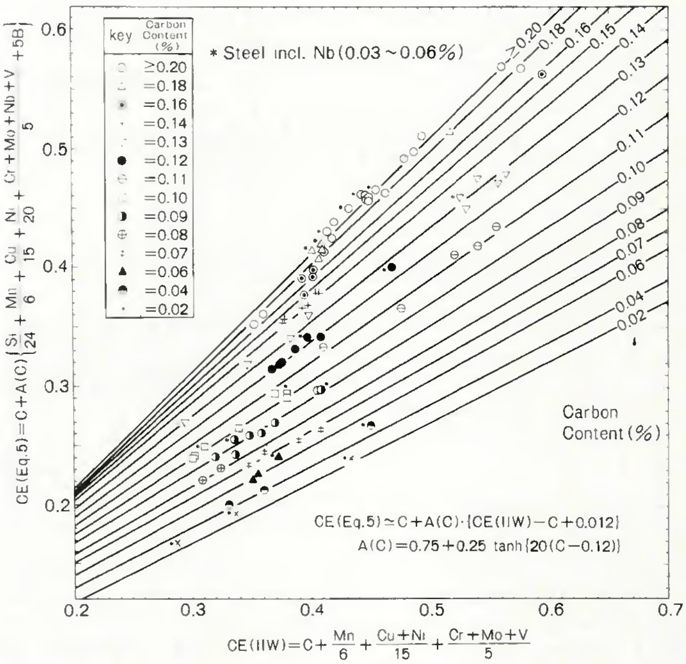


Fig. 14—Relationship between CE(IIW) and $CE_{eq(5)}$

are shown in Fig. 2; and B_s' is an imaginal increment of the slit length due to the elastic reaction of a steel specimen. B_s' is 304 mm (12 in.) for type I specimens and 446 mm (17.6 in.) for type II.

Generally speaking, r_f is 70 kgf/mm^2 · mm (26,300 lbf/in.^{3}) for the severest restraint and about 40 kgf/mm^2 · mm (15,000 lbf/in.^{3}) for ordinary restraint (Ref. 10). The restraint intensity, R_F, is given by the product of r_f and the plate thickness, h, in the case of thin plate and pipe. However, an FEM analysis of three-dimensional elastic test pieces revealed that R_F did not increase in proportion to h in a greater thickness region (Ref. 13). The approximate relationship between R_F, r_f, and h is given as:

$$R_F = 71\, r_f \{\arctan (0.017\, h) - (h/400)^2\} \qquad (A2)$$

This relation is graphically shown in Fig. 10.

Cooling Time to 100°C

The cooling time to 100°C (212°F) after the completion of welding under various conditions is available in the literature (Ref. 14). For the limited case of local preheating by electric heaters, times are given in Fig. 11 for 1,700 J/mm (43,180 J/in.) of heat input and in Fig. 12 for 3,000 J/mm (76,200 J/in.).

New Carbon Equivalent

The carbon equivalent proposed—CE as calculated from equation (5)—has an accommodation factor, A(C), which is a function of the carbon content of the steel as:

$$A(C) = 0.75 + 0.25 \tanh \{20(C - 0.12)\} \qquad (6)$$

The graphic relation of A(C) to carbon content, C, is given in Fig. 13.

The CE as calculated from equation (5) can be rewritten as:

$$CE_{eq.(5)} \simeq C + A(C) \cdot \{CE\ (IIW) + 0.012 - C\} \qquad (A3)$$

The relationship between $CE_{eq.(5)}$ and CE(IIW) was examined for various types of steel, including those listed in Tables 2 and 3 and others. It is seen in Fig. 14 that equation (A3) holds for steels having Nb less than 0.02% and Si ranging from 0.24 to 0.48%.

Equation (A3) implies that CE(IIW) values equal to $CE_{eq.(5)}$ significantly increase in the region of lower carbon content as shown in the dotted lines in Fig. 13. The present study showed that $CE_{eq.(5)}$ is more appropriate in assessing steel's susceptibility to cold cracking than CE(IIW). It follows that steel with a low carbon content is considered less susceptible to cold cracking, even when the CE(IIW) of the steel is high.

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