On the Fillet Weld Cracking of 50 kg/mm² Grade High Strength Steels†
—On the Heel-Crack—

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Abstract

It is generally known that the majority of fillet weld cracks are toe cracks underbead cracks and so on. But we have found unusual crack in the fillet welds of 50 kg/mm² grade high strength steels. The crack occurred at the heel—opposite side of the toe—of fillet weld. Therefore we refer to them by the name of "Heel-Crack" in this paper. We have carried out various experiments to make clear the characteristics of the crack and the causes of the crack formation, and also we have established a practical preventive method for the crack which based on these test results. The test results are summarized here as follows:

(1) Heel-cracks are located at the heel of fillet welds and they are hardly detectable by inspection methods such as visual observation and magnetic particle inspection.

(2) It has been difficult to reproduce the heel-cracks by well known weld cracking tests such as C. T. S. test and Reeve cracking test. But we have developed Non-restraint T type Cracking Test which can reproduce heel-cracks succssfully.

(3) Heel-crack is a low temperature crack which occurs at temperature below 100°C.

(4) Main factors which affect the heel-crack formation are the cooling process of the weld, rigidity and hydrogen in the weld.

(5) Many 50 kg/mm² grade high strength steels are susceptible to the formation of heel-cracks. But semi-killed steels seem somewhat less susceptible to heel-cracks than killed steels.

(6) Crack sensitivity is increased by increasing the carbon equivalent and/or the maximum hardness at underbead.

(7) Heel-crack could be prevented by preheating or controlling the bead length. To prevent the heel-crack, higher preheating temperature and longer weld bead are preferable.

1. Introduction

Root cracks, toe-cracks and underbead cracks known as crack defects are found in fillet weld. A new type of defect called "heel-crack", which is something different from root cracks, was found in the opposite side of the toe as shown in **Photo. 1.**

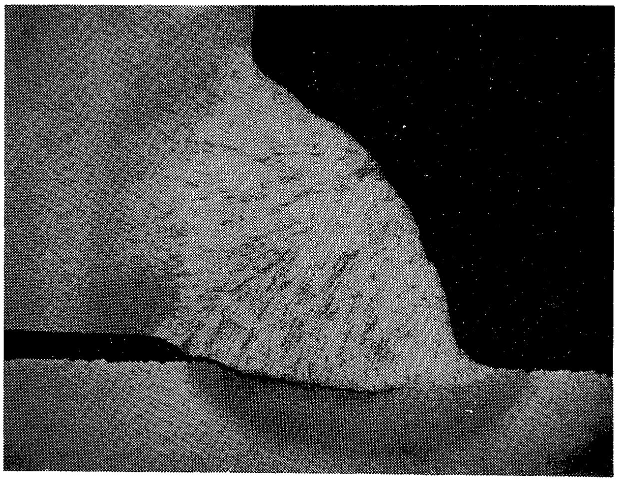

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Photo. 1 Typical Example of Heel-Crack.

This type of crack was a relatively shallow longitudinal crack along the weld bead and it was less than 2 or 3 mm in the depth. Cracks propagated along the fusion line in the heat affected zone, and it appears that the crack was initiated by the pulling apart of the welded plates. One of the characteristic features of this crack was that the crack was found when the plates, which are less than 12 mm, were welded. Effects of hydrogen cannot be discounted, as it is possibly related to the initiation of the crack, because the crack was found in the fillet weld even when ilmenite or low hydrogen type electrodes were used in welding.

A heel-crack, in the hidden underbead spots cannot be detected by visual inspection. Reproduction by the generally known fillet weld crack tests is difficult. Thus few cracks of this sort have ever been systematically studied. In order to devise a method for reproducing and prevention of heel-cracks, some factors related to the initiation of the crack were studied.

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2. Method for Reproducing the Heel-Crack and Factors related to the Crack Initiation

2-1 Development of Test Method

A test method must be established for reproducing heel-cracks. For this purpose, fillet weld cracking tests, C. T. S. tests, Reeve crack tests and cruciform fillet weld cracking tests were used. The dimensions of the test specimens are shown in **Fig. 1.**

C. T. S. test was carried out on 12 mm 50 kg/mm^2 grade high strength steel under various conditions. **Table 1** shows the chemical composition of the plate. **Fig. 2** gives **(a)** underbead crack; **(b)** root crack in the upper plate; and **(c)** weld metal crack. There were no heel-cracks.

In Reeve crack tests, as shown in **Fig. 1 (b),** the test piece was tightly bolted to a 50 mm thick restraining plate, so that the restraint is greater than in C.T.S. test. For this reason, the cracks in Reeve crack test are slightly larger than in C. T. S. test, but the crack shape was almost the same. The cruciform fillet weld cracking test has recently been used as a test method for low temperature cracks in the first layer of a fillet weld, but in this experiment no crack was found by this method.

As it is difficult to reproduce heel-cracks by the conventional fillet weld cracking tests, test pieces, having a geometrically similar shape and with the actual welding joint in which heel-cracks were observed, were made as shown in **Fig. 3.** Tests were made by placing three short beads intermittently on the T-type 12 mm plate test piece (Table 1). Welded specimens were left for 24 hours after welding and checked for cracks. Heel-cracks were observed in each bead. However, in a Tee joint cracking test in which restraint beads were placed on the opposite side of test beads before the test bead was placed no heel-crack appeared as shown in **Fig. 3 (b),** even though the test was made with T-type test plate.

In the above tests a no-restraint T-type fillet weld

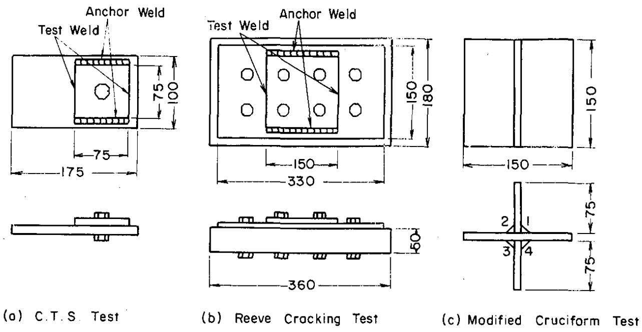

Fig. 1. Fillet Weld Cracking Test Assembly.

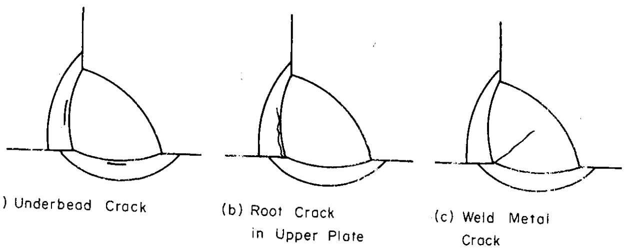

Fig. 2. Crack Shape in C. T. S. Test.

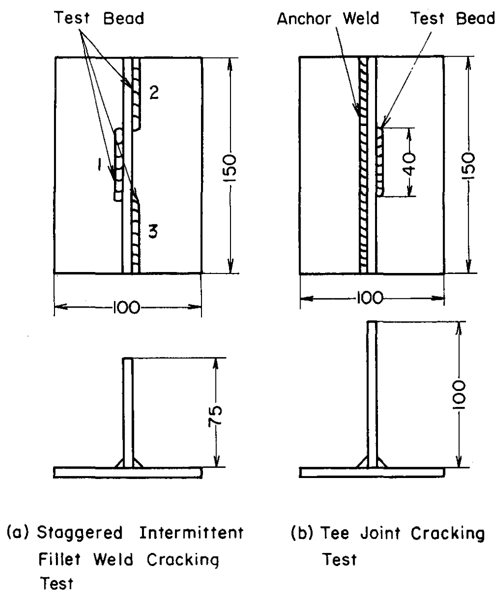

Fig. 3. Tee Joint Weld Cracking Specimen.

Table 1. Chemical Composition and Mechanical Properties of Test Plates

Thickness (mm)	Chemical Composition (%)							Inclusions			Mechanical Properties		
	C	Si	Mn	P	S	Nb	Ceq	dA 60×400	dB 60×400	dC 60×400	Yield Point (kg/mm^2)	Tensile Strength (kg/mm^2)	Elongation (%)
12	0.16	0.49	1.38	0.025	0.014	--	0.410	0.095	0	0.129	44	57	30
								0.092	0	0.066			
								0.029	0	0.079			
30	0.15	0.46	1.39	0.017	0.009	0.03	0.401	0.025	0	0.029	42	55	33
								0	0	0.025			

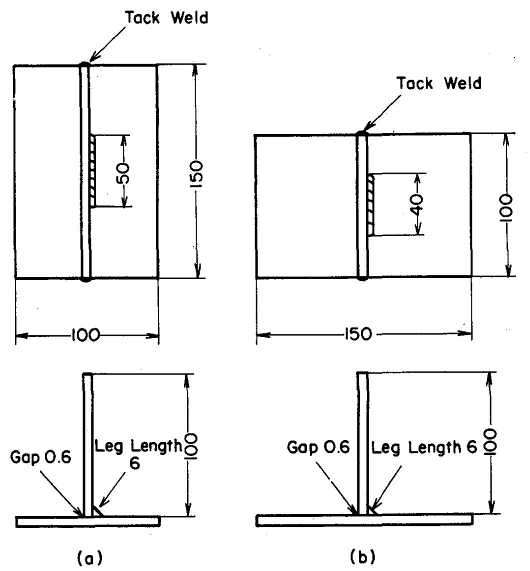

Fig. 4. Standard Non-restraint T type Cracking Test.

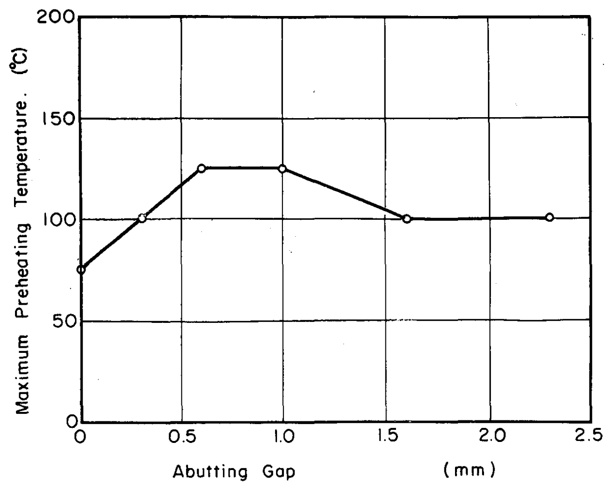

Fig. 5. Maximum Preheating Temperature to Prevent Heel-Cracking Against Abutting Gap.

cracking test piece (called T-type test piece in this report) was developed to which vertical plate and horizontal plate was tack welded at both ends and then test bead was placed as shown in **Fig. 4.** There was no difference in the cracking tendency between (a) placing the test bead in the longitudinal direction of the test piece and (b) placing the test bead in the cross-sectional direction, but both had a larger cracking tendency than the staggered fillet weld cracking test, and were considered to be appropriate for standard test pieces for investigation of heel-cracks. The results of various preliminary tests showed that the increase of the weld bead length of fillet weld tended to off-set heel- cracks. Therefore, the welding standard for heel-crack test pieces was determined as 40 to 50 mm for bead length with fillet weld leg size of 6 mm.

In order to investigate the relation between the abutting gap with the horizontal plate and vertical plate and the heel-crack, the pre-heating temperature for preventing the heel-cracks to various abutting gaps was studied using a 12 mm test plate, **Table 1,** and test piece, **Fig. 4 (b).** The results of the experiment in **Fig. 5** show that the pre-heating temperature for preventing heel-cracks was high and that the cracking tendency at 0.6 to 1.0 mm at abutting gap was greater. Therefore 0.6 mm was assessed as the standard abutting gap. Low hydrogen type electrodes were used in the following experiments unless otherwise specified.

2-2 Time for Heel-Cracking

In order to successfully investigate cause and prevention of heel-cracking it is important to know the exact time of cracking. The results of tests showed that heel-cracks were prevented by pre-heating. This indicates that heel-cracking is a phenomena of low temperature cracking. The range of heel-cracking temperatures was studied to investigate the time of heel-cracking by holding the specimen for a certain time at certain temperatures in the weld thermal cycle. Mechanical measurements were also taken for determining exact time of heel-cracking.

The cracking tendency by the isothermal treatment at 130°C in the course of the descending welding thermal cycle was studies, and the results are shown in **Table 2.** Heel-cracking was not observed when isothermal treatment was conducted for more than 30 minutes at 130°C. It is logical to assume that heel-crack definitely occur at certain temperatures below

Table 2. Effect of Isothermal Treatment at 130 C on Heel-Cracking

Holding Time at 130°C (min)	Degree of Heel-Cracking	Max. Hardness at Underbead (Hv)	Remarks
0	4/4	390	Initial Temp. of Specimens 20°C
5	2/4	395	Hydrogen Content 13.4 cc/100gr
30	0/4	392	Degree of Heel-Cracking $= \frac{\text{Cracked Specimens}}{\text{Inspected Specimens}}$
60	0/4	397	After Isothermal Treatment, Specimens were Water Cooled.

130°C. In this experiment, electrodes, which were intentionally moistened were used, therefore hydrogen content in the weld metal was large. Tests showed that longer isothermal treatment resulted in less heel-cracking because of the small hydrogen content, and that post-heating was effective in preventing heel-cracks.

When the weld test piece was reheated to 400°C from a certain temperature below 400°C in the descending course of the weld thermal cycle, great cracking tendency was observed at the reheating temperature starting below 70°C as shown in **Table 3.** The results are in good agreement with the results of the mechanical measurement described below.

Mechanical measurements traced the deflection of the vertical plate due to the thermal shrinkage by a strain gauge as shown in **Fig. 6.** This measuring system is capable of detecting as deflection of 40 μ at the minimum (0.04° in terms of angle). This measuring system simultaneously records the time-deflection curve and the time-temperature curve, and the crack is detected by the discontinuing line on the time-deflection curve as shown in **Fig. 7.** The maximum temperature on the time-temperature curve is about 900°C, but this does not detect the thermal cycle of the heel in the fillet weld. The discontinued point on the

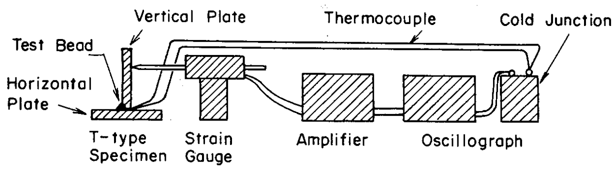

Fig. 6. Schematic Diagram of Crack Detection Apparatus.

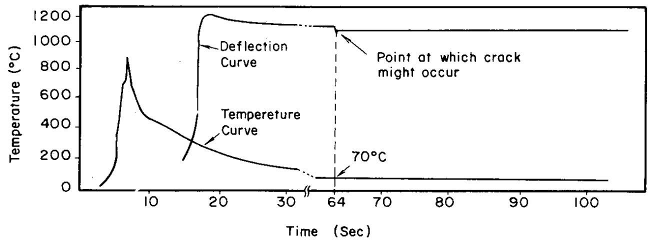

Fig. 7. Example of Time-Temperature and Time-Deflection Measurement.

time-deflection curve, which may corespond to cracking, was observed at 70°C. There may be no temperature difference in the relatively low temperature range between the detecting spot and the heel in the fillet weld.

These results confirm that heel-cracking occurs in low temperatures at below 100°C.

Table 3. Effect of Reheating to 400 C on Heel-Cracking

Initial Temp. of Specimen (°C)	Peak Temp. (°C)	Starting Temp. of Reheating (°C)	Results	Remarks
	--	--	x	
	--	--	x	
	520	100	0	
	340	100	0	
50	550	100	x	Reheating Temp. 400°C
	440	90	0	Holding Time at Reheating Temp. 1 min.
	1200	50	x	
	1000	50	x	0 No Crack
	900	50	x	
	--	--	x	x Heel-Crack
	--	--	x	
	700	300	0	
	800	300	0	
	1000	250	0	
	800	230	0	
−20	1200	120	0	
	800	110	0	
	670	70	x	
	700	75	x	
	680	50	x	
	620	50	x	
	420	40	x	

2-3 Effects of Micro-Structure and Hardness

It is confirmed that heel-cracking occurs at a low temperature below 100°C. In the case of low temperature cracking, micro-structure (hardness), hydrogen, restraint (stress) are the possible causes for initiating the crack. The micro-structure is closely related to the hardness, and is affected by the chemical composition and the cooling process in welding, as authorities have pointed out in many reports. Here attention was concentrated on the cooling process. Micro-structure and hardness tests were also tested.

The weld thermal cycle on which the heel-crack was observed, was recorded and plotted in SH-CCT diagram (Continuous Cooling Transformation Diagram of Synthetic Heat Affected Zone) as shown in **Fig. 8.** Although there is a slight difference in the thickness of the plates, the heel-crack was observed in the cooling process that passed at the top of the ferrite area. The micro-photograph nere the heel-crack is shown in **Photo. 2.** In this case, the maximum hardness was 380 Hv. The heel-crack was not observed when the cooling curve was deviated to the longer time side on the SH-CCT diagram with maximum hardness 320 Hv. From these facts, it may be concluded that there is a certain hardness limit which governs heel-cracking.

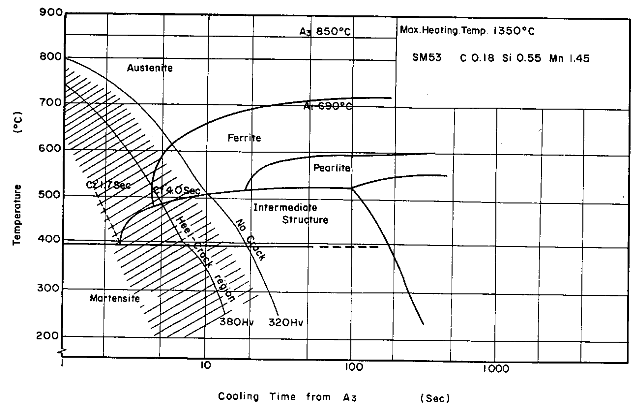

Fig. 8. Cooling Curve in Relation to Heel-Cracking.

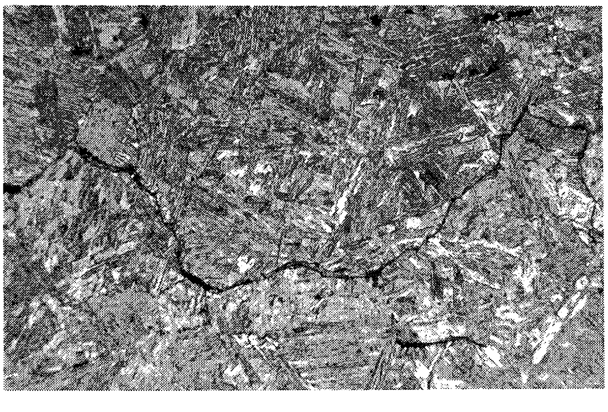

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Photo.2 Microstructure Adjacent to Heel-Crack.

It has been established that the micro-structure of the heat affected zone is closely related to the cooling time between 800°C and 500°C in the cooling process of the descending course of the weld thermal cycle. Inagaki et al[1)] reported that under certain assumptions, the cooling time from 800°C to 500°C is proportional to the square of the width of the partial solid solution range in the heat affected zone, where the length of the range is called the characteristic distance. The relation between the local cooling time of the heel in the fillet weld and the degree of the heel-crack was estimated after determining the characteristic distance as shown in **Fig. 9.** If the microstructure was the dominent factor for the crack, the crack would be obserserved in all the test pieces. In non-restraint T-type weld test pieces, heel-cracking was observed but no crack was observed in restraint type and C. T. S. type weld test pieces. Therefore it is suggested that crack sensitivety is not entirely dependent on the micro-structure, and that the dynamic factors (see the section on restraint) should also be investigated. The longer the cooling time from 800°C to 500°C, the lesser the heel-crack in non-restraint T-type weld test piece.

A few studies have been made concerning lamellar tear recently[2)]. It is reported that cracking propagates along the silicate inclusions, and the existence of large amounts of non-metallic inclusions would cause cracking. Once cracking was initiated, it is possible that cracking will propagate along the non-metallic inclusions and there were some examples of such propagation of a crack in our study. Nevertheless, little non-metallic inclusions were observed in the steels used in

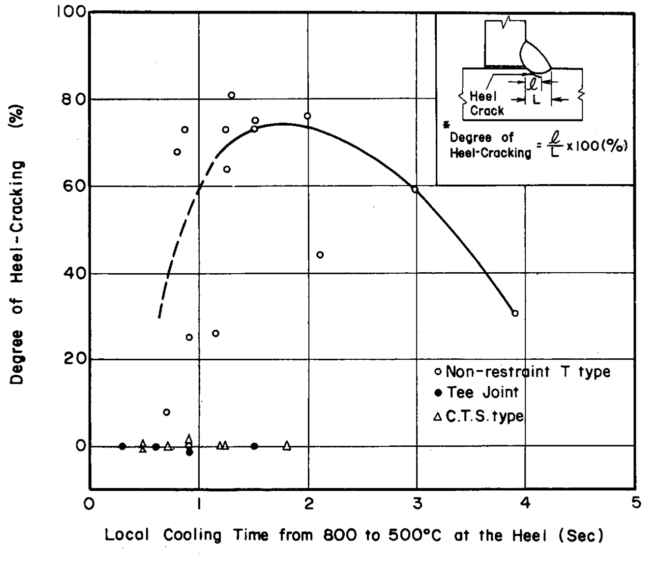

Fig. 9. Relation between Cooling Time from 800 to 500°C and Heel-Cracking.

these tests but there was a case in which the crack propagated along the gain boundary as shown in **Photo. 2.** Thus non-metallic inclusions may not be related to the initiation of cracking.

2-4 Effects of Restraint

As already described in section 2-3, it is difficult to explain the tendency of heel-cracking from the factor of micro-structure in non-restraint T-type weld test pieces only, therefore dynamic factors should also be studied. The relation between the crack shape and the pre-heating temperature for preventing cracks in shown in **Table 4** when 30 mm plate T-type test piece was used (Table 1). The thickness of the vertical plate and the restraint condition were changed while keeping the thickness of the horizontal plate at 30 mm. Since the plate thickness of the horizontal plate was kept constant, the micro-structure of the heel was not affected by the various conditions. Nevertheless, a heel-crack was observed when the vertical plate was thin and there was no restraining bead on the opposite side of the test bead. Furthemore, in the case of a Tee joint on which a restraining bead was placed, a root crack was observed in the vertical plate. The pre-heating temperature for preventing the crack is 75°C.

The results of the experiment described above indicated that the rigidity to lateral bending of the vertical plate has a large effect upon heel-cracking. The fillet weld cracking tendency was investigated by varying the dimensions of the vertical plate and the horizontal plate, choosing appropriate values for rigidity to lateral bending (I_H), rigidity of logitudinal bending (I_V) of the vertical plate, and rigidity of the horizontal plate (I). **Fig. 10 (a)** shows the dimensions of the test pieces and **Table 5** indicates the value of the moment of inertia under varying conditions. The 30 mm plate in **Table 1** was used for this experiment, and the standard bead length and leg size were respectively 40 mm and 6 mm. In the crack inspection after

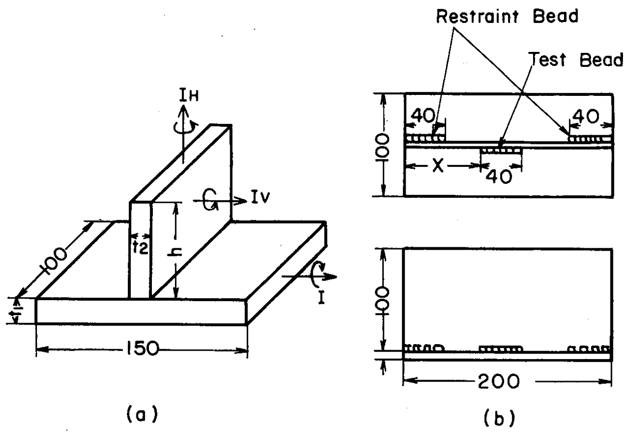

Fig. 10. Dimension of Test Piece.

Table . 4. Effect of Thickness of Vertical Plate and Restraint on Fillet Weld Cracking

Thickness of Vertical Plate	Non-Restraint T type		Tee Joint	
	Preheat to Prevent Cracking	Crack shape	Preheat to Prevent Cracking	Crack Shape
30 mm	<R. T.		75°C	Root Crack in Vertical Plate
12 mm	75°C	Heel-Crack	50°C	Root Crack in Vertical Plate

(Note) Horizontal Plate Thickness 30 mm

Table 5. Dimension of Test Piece

Specimen	t_1 (mm)	t_2 (mm)	h (mm)	I_H (mm^4)	I_V (mm^4)	I (mm^4)
1	30	10	100	0.8×10^4	8.3×10^5	3.3×10^5
2	30	15	87	2.5×10^4	8.3×10^5	3.3×10^5
3	30	20	79	5.3×10^4	8.3×10^5	3.3×10^5
4	30	30	69	15.8×10^4	8.3×10^5	3.3×10^5
5	30	10	46	0.4×10^4	8.3×10^4	3.3×10^5
6	30	20	37	2.5×10^4	8.3×10^4	3.3×10^5
7	30	30	32	7.2×10^4	8.3×10^4	3.3×10^5
8	10	10	100	0.8×10^4	8.3×10^5	1.3×10^4
9	10	20	37	2.5×10^4	8.3×10^4	1.3×10^4
10	10	30	32	7.2×10^4	8.3×10^4	1.3×10^4

completion of welding the test pieces were left for 20 hours to air cool and cross-sectional part of bead was checked for cracks. **Fig. 11** shows the results of the experiment.

I_H representing the rigidity of lateral bending, namely the thickness of the vertical plate was small when a heel-crack was observed. The cracking tendency was increased, when the test pieces were precooled at $-25°C$. When I_H became smaller relative to I or I_V neither heel-crack nor other cracks were found in the vertical plate.

In the experiment above, the rigidity of lateral bending reached limit at the maximum 30 mm thick plate. Thus 12 mm plate was used (Table 1), and the ralative position of the test bead was changed to the two restraint beads on the edge of the opposite side of the test bead as shown in **Fig. 10 (b).** It was possible to reproduce a large rigidity of lateral bending by changing the rigidity of the vertical plate by placting the test bead closer to the restraint beads. Welding conditions and crack inspection were the same as in the experiment above. The results are shown in **Fig. 12.** When the restraint beads are placed on the opposite side to the test bead (which corresponds to the large I_H) X=20 mm, 140 mm a root crack was observed in the vertical plate. When the relative distance between the test bead and the restraint beads was increased (I_H was decreased) to make X=60 to 120 mm, a heel-crack was observed, but in the transient range (X=30 mm, 130 mm) where the crack shape varied from a heel-crack to a root crack in the vertical plate, no crack was observed.

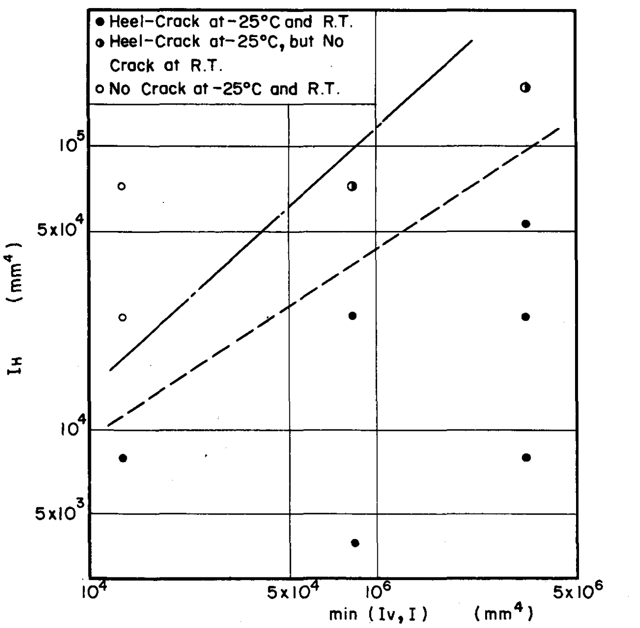

Fig. 11. Relation between Geometricat Moment of Inertia and Heel Cracking.

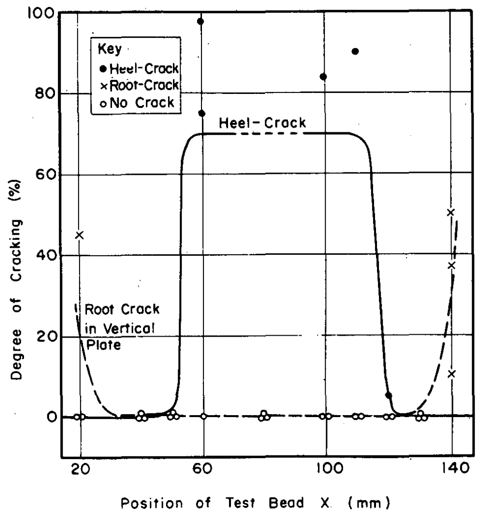

Fig. 12. Degree of Crack vs. Position of Test Bead.

The qualitative relation between the rgidity of the plate and the internal stress in the heat affected zone was studied. The stress, in the finally solidified part in a fillet weld, resulted from the restrictive action of the shinkage through the rigidity of the plate by the restraint of the previously solidified bead. If the rigidity of lateral bending of the vertical plate is small, it will reduce the horizontal component of contraction and the notch shape of the heel which is sensitive to cracking will produce a heel-crack in the horizontal plate. If the horizontal deflection of the vertical plate is restrained by increasing the rigidity of lateral bending of the vertical plate, it will generate a horizontal stress component overcoming the notch effect in the heel and results in a root crack in the vertical plate. There is a range where no crack was generated in certain ratio between the rigidity of lateral bending and that of longitudinal bending. This is probably a phenomenon caused by the other factors.

2-5 Effects of Hydrogen

As already described in section 2-2, the heel-crack is one of the low temperature cracks which occurs below 100°C, which indicates that hydrogen may have some relation to the crack. The following experiment was conducted to check this. The martensite transformation in the heat affected zone by the weld thermal cycle is nearly completed by 200°C, and changing the cooling rate below 200°C of the temperature in the heat affected zone means changing the evolution of diffusible hydrogen into the heat affected zone without micro-structural change. Using 12 mm thick plate, **Table 1,** a small T-type test piece was made, as shown in **Fig. 13,** to improve the thermal response. The heel-crack tendency was investigated by changing the cooling rate of the test piece when the temperature

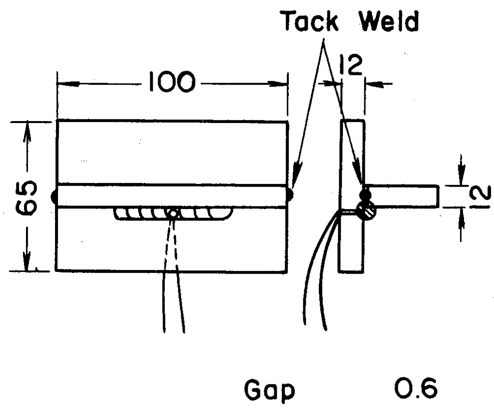

Fig. 13. Dimension of Specimen.

of the fusion line became 200°C in cooling by the following operation.

(A) Kept at 250°C for 3 minutes in the electric furnace and air cooled.
(B) Air cooled.
(C) 17 hours immersion in alcohol at 0°C.
(D) 17 hours immersion in alchol at −25°C.
(E) 17 hours immersion in alcohol at −50°C.
(F) 17 hours immersion in alcohol at −100°C.

For the measurement of the cooling curve, a thermocouple was set at the center of the bead length under the bead area of the horizontal plate. Heat-resistant cement was used to cover the measuring spot for preventing intrusion of alcohol.

The results of the experiment are shown in **Fig. 14.** There is no difference in the maximum hardness by the various cooling rates, and it appears doubtful that the micro-structural change was caused by the cooling method of (A), (B) ---- (F). Nevertheless, as there is a difference in the heel-cracking tendency, it may be regard as the effect of hydrogen. In other words, if the cooling rate is small (operation A), hydrogen will

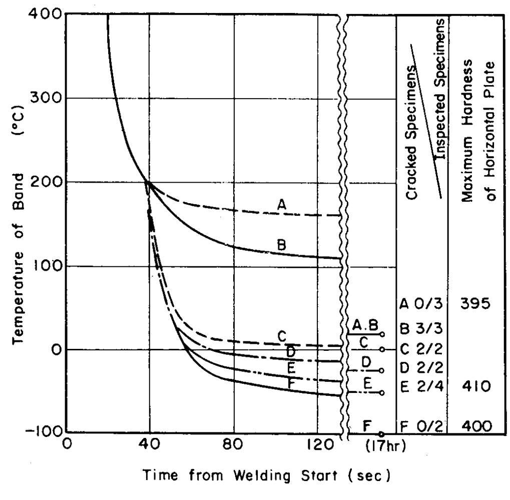

Fig. 14. Relation between Cooling Rate below 200°C and Heel Cracking.

be evolved, and if the cooling rate is large and the test piece is kept at low temperature (Operation F), hydrogen evolution will be fixed and no heel-crack will be observed. It is possible to conclude from the results of the experiment that the heel-crack is one of the low temperature cracks due to hydrogen.

For investigating the effect of the welding electrode upon the heel-crack, the standard test piece, **Fig. 4(b),** was made using 12 mm thick plate, **Table 1.** The degree of cracking was investigated at various preheating temperature using low hydrogen type and ilumenite type electrodes. As is shown in **Fig.15,** the degree of cracking decreased the pre-heating temperature was raised, and the pre-heating temperature for preventing the heel-cracks was 125°C in all cases. But there was a difference between the two types of electrodes in the degree of cracking for 75°C and 100°C in the pre-heating temperature. This may be due to the fact that there is a difference between the low hydrogen type electrode and the ilmenite type electrode not only in hydrogen content but also in the yield stress and its cross-sectional shape of the fillet weld, which combine in a complicated manner to influence the heel-cracking tendency.

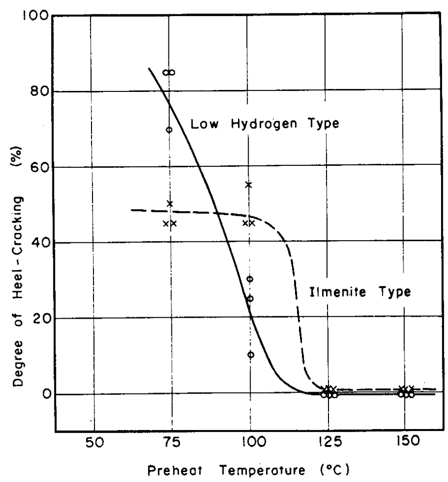

Fig. 15. Comparison of Heel-Cracking between Low Hydrogen and Ilmenite Type Electrode.

2-6 Effects of Steel Types and Chemical Compositions

Initially a heel-crack was found in a relatively thin plate of SM53C. Consequently SM53C was mainly used in the tests. The tests were conducted for determining whether the heel-crack is peculiar to SM53C or common to other steels having about the same strength as SM53C. The following 14 charges were selected for the test, rolled steels for welded structures SM50, SM50Y and SM53 of about 12 mm thick plate; various degree of deoxidized conditions killed and semi-killed

Table 6. Chemical Composition and Mechanical Properties of Test Plates

Steel	Killed or Semi-Killed	Plate Thick. (mm)	Chemical Compositions* (%)										Yield Pt. (kg/mm^2)	Tensile St. (kg/mm^2)	Elong. (%)
			C	Si	Mn	P	S	Ni	Cr	Nb	Al	Ceq**			
SM50A (A)	Killed	12	0.20	0.38	1.37	0.019	0.008	0.01	0.02	tr.	0.032	0.447	39	58	25
SM50B (B)	Killed	12	0.16	0.40	1.24	0.017	0.020	0.01	0.02	tr.	0.035	0.388	39	56	25
SM50B (C)	Killed	12	0.16	0.40	1.33	0.011	0.006	0.01	0.02	tr.	0.008	0.394	38	54	24
SM50B (D)	Killed	10	0.16	0.34	1.34	0.021	0.018	0.02	0.04	tr.	0.027	0.405	41	56	21
SM50YB (E)	Semi-Killed	12	0.19	0.02	1.32	0.022	0.015	0.01	0.02	0.03	0.011	0.417	45	58	26
SM50YB (F)	Semi-Killed	14	0.16	0.05	1.32	0.013	0.016	0.02	0.17	0.01	0.004	0.416	38	52	23
SM50YB (G)	Killed	12	0.16	0.16	1.10	0.015	0.015	0.01	0.02	0.02	0.023	0.354	41	54	26
SM50YB (H)	Killed	12	0.20	0.23	1.32	0.016	0.011	0.01	0.02	0.01	0.021	0.436	44	60	26
SM50YB (I)	Semi-Killed	11.5	0.18	0.02	1.43	0.025	0.038	0.10	0.055	0.008	0.009	0.430	41	51	22
SM50YB (J)	Semi-Killed	25.4	0.17	0.033	1.27	0.030	0.030	0.13	0.069	0.030	0.010	0.397	37	58	22
SM53B (K)	Killed	12	0.18	0.40	1.25	0.016	0.015	0.01	0.02	tr.	0.035	0.411	37	55	27
SM53B (L)	Killed	12	0.16	0.33	1.32	0.025	0.025	0.18	0.11	tr.	0.026	0.420	39	59	26
SM53C (M)	Killed	12	0.18	0.49	1.45	0.029	0.018	0.01	0.03	tr.	0.035	0.449	46	62	38
SM53C (N)	Killed	25	0.16	0.49	1.42	0.017	0.019	0.01	0.02	0.03	0.041	0.420	41	56	38

(Note) * Check Analysis

** $Ceq = C + \frac{1}{6}Mn + \frac{1}{24}Si + \frac{1}{40}Ni + \frac{1}{5}Cr + \frac{1}{4}Mo + \frac{1}{14}V$ (%)

steels; various carbon equivalent; and various contents of Nb, Al and other elements. The check analysis and mechanical properties of these steels are shown in **Table 6.**

In the tests, the cracking tendency at atomospheric temperature, the maximum hardness survey at underbead, and the pre-heating temperature for preventing the crack were studied. The results are shown in **Table 7.** The test results are summarized as follows;

(1) The heel-crack is not peculiar to SM53C, but it is common to 50 kg/mm^2 grade high strength steels. Semi-killed steels seem less sensitive to the heel-cracks than killed steels.

(2) Heel-cracking tendency increases with higher carbon equivalent and underbead hardness (See **Fig. 16**).

Table 7. Results of Non-Restranit T type Cracking Test on Various Steel Plates

Steel	Killed or Semi-Killed	Plate Thick. (mm)	Ceq* (%)	Degree of** Heel-Cracking at 20°C	Max. Hardness at Underbead (Hv)	Preheat Temp. to Prevent the Crack (°C)
SM50A (A)	Killed	12	0.447	2/7	386	75
SM50B (B)	Killed	12	0.388	3/10	412	50
SM50B (C)	Killed	12	0.394	2/7	317	75
SM50B (D)	Killed	10	0.405	3/10	306	50
SM50YB (E)	Semi-Killed	12	0.417	2/15	306	25
SM50YB (F)	Semi-Killed	14	0.416	0/7	313	−20
SM50YB (G)	Killed	12	0.354	1/11	286	25
SM50YB (H)	Killed	12	0.436	4/7	396	125
SM50YB (I)	Semi-Killed	11.5	0.430	0/8	299	20
SM50YB (J)	Semi-Killed	25.4	0.397	0/8	353	20
SM53B (K)	Killed	12	0.411	2/10	358	50
SM53B (L)	Killed	12	0.420	6/7	391	100
SM53C (M)	Killed	12	0.449	4/4	418	--
SM53C (N)	Killed	25	0.420	4/4	396	--

(Note) * $Ceq = C + \frac{1}{6}Mn + \frac{1}{24}Si + \frac{1}{40}Ni + \frac{1}{5}Cr + \frac{1}{4}Mo + \frac{1}{14}V$ (%)

** $\text{Degree of Heel-Cracking} = \frac{\text{Cracked Specimens}}{\text{Inspected Specimens}}$

(3) Heel-cracks can be prevented by pre-heating, but the pre-heating temperature must be raised with higher carbon equivalent and the maximum underbead hardness,
(4) For a low Si content semi-killed steels, the cracking tendency is low and also for a relatively high Si content within the range of killed steels indicating that there is no clear relation between the Si content and the cracking tendency (See **Fig. 17**).
(5) Nb, Al and small quantities of other elements do not have any influence on the heel-crack.

It became clear that a heel-crack was observed in 50 kg/mm^2 grade high strength steels of which, in Japan, are mostly killed steel. Consequently sufficient care must be paid when using steels of this type.

There is some difference in the cracking tendency between killed steels and semi-killed steels. The only distinct difference between these two types of steels is the Si content. The chemical compositions of the surface layer where the heel-crack is less, and the center of the plate were investigated, but there was no difference, between them as shown in **Table 8.** As it was impossible to obtain positive conclusions on the difference, research is being continued.

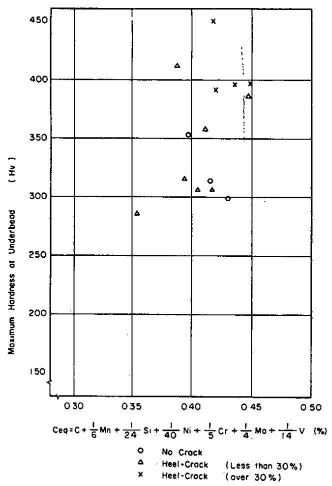

Fig. 16. Relation between Carbon Equivalent, Maximum Hardness at Underbead and Heel-Cracking.

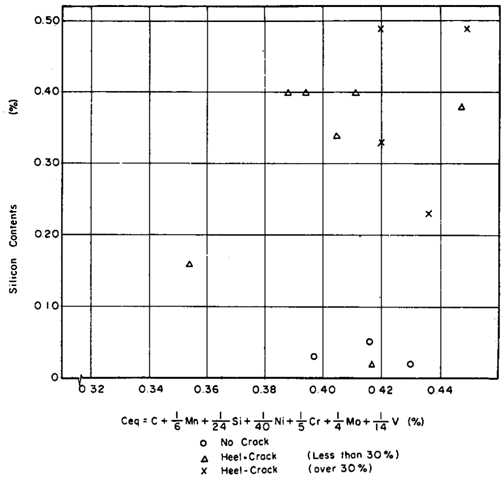

Fig. 17. Relation between Carbon Equivalent, Silicon Contents and Heel-Cracking.

2-7 Effects of Bead Length

In the experiments, the bead length was kept constant 40 to 50 mm. For the purpose of investigating the affect of the bead length on the heel-cracking tendency, an experiment was conducted by changing the bead length from 20 to 200 mm using 12 mm thick plate. The test pieces used are shown in **Fig. 4 (a)** and the dimension of the horizontal plate is 150×300 mm. The test pieces were pre-cooled at −25°C. The test results are shown in **Fig. 18.** No heel-crack was observed when the bead length is longer than 80 mm.

The maximum hardness of the underbead along the bead direction did not show any change as long as 100 mm and the maximum hardness at the center was more than 405 Hv. Consequently it is difficult to say that the increase in the bead length resulted the less hardening effect of the heat affected zone and decreased the heel-cracking. A thermocouple was welded on the crater to measure the cooling rate in welding. The cooling time from 100°C to 50°C for 100, 80, 60, 40 mm bead length were respectively 53, 48, 32 and 20 seconds. The effect of the bead length is to change the cooling process in the low temperature range so as to activate the evolution of diffusible hydrogen which affects the crack initiation.

Table 8. Results of Chemical Analysis at Surface and the Middle of Semi-Killed Steel Plates

Steel	Plate Thick. (mm)	Location	Chemical Composition (%)				
			C	Si	Mn	P	S
SM50YB (E)	12	Surface	0.19	0.02	1.33	0.024	0.016
		Middle Thickness	0.20	0.02	1.33	0.024	0.019
SM50YB (I)	11.5	Surface	0.17	0.02	1.39	0.020	0.037
		Middle Thickness	0.18	0.02	1.40	0.021	0.037

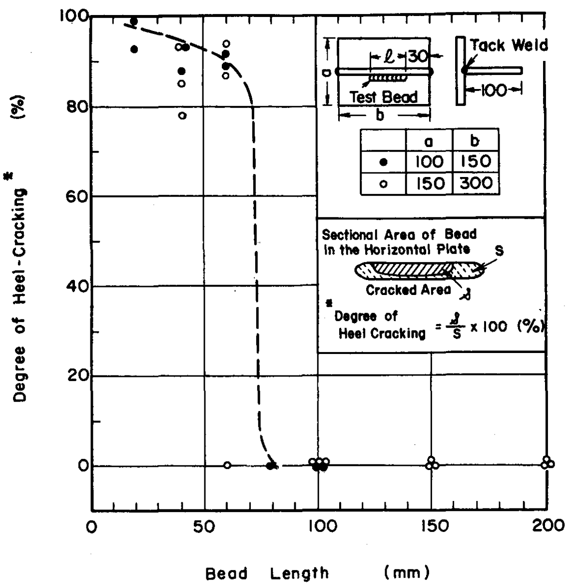

Fig. 18. Effect of Bead Length on Heel-Cracking.

3. Prevention of Heel-Cracks

The heel-crack observed in the fillet weld is relatively shallow 2 or 3 mm. It does not propagate to the direction of thickness. Welding techniques to prevent heel-cracking were studied in order to produce welded structures without weld defects.

As has been already described the heel-crack is a low temperature crack observed in 50 kg/mm^2 grade high strength steel after the cooling process passing the top of the ferrite area on the SH-CCT diagram, and the factor involved for the crack initiation are the rigidity of the material and the hydrogen content. Since the rigidity of frame work members depend on thickness and dimensions, some consideration may be given when designing for preventing heel-cracks, but it is difficult to control in the actual construction. On the other hand, in order to eliminate the effects of hydrogen, it may be possible to activate the hydrogen evolution by changing the cooling process in welding by pre-heating or post-heating. Pre-heating temperatures required for preventing heel-crack for various types of steels are shown in **Table 7.** Semi-killed steels do not nesessarily require pre-heating, but killed steel requires higher pre-heating temperatures with increasing carbon equivalent. In short, appropriate pre-heating can prevent heel-cracks.

As preheating can prevent heel-cracks post-heating may also prove to be a preventative measure. But post-heating loses its effect unless it is conducted before the the temperature reaches below 100°C in the descending course of the weld thermal cycle. Consequently, pre-heating is essentially more practical for preventing heel-cracks.

The long bead is also effective for preventing heel-cracks, see section 2-7.

4. Summary

The heel-crack is one of the low temperature cracks observed along the fusion line of the horizontal plate of the fillet weld. The cooling process of the weld, the rigidity of the member, and the residual hydrogen, are all factors related to heel-cracking and the cracking tendency will differ according to changes in these three factors.

It is difficult to reproduce the heel-crack by an ordinary C. T. S. test, however the T-type test piece developed in this experiment proved effective for the reproduction of the heel-crack. The results of the various tests of T-type test piece 50 kg/mm^2 grade high strength steels may be summarized as follows:

(1) Heel-crack occurs below 100°C.
(2) Heel-crack is observed in the test pieces when a cooling process passes the top of the ferrite area on the SH-CCT diagram, but the effects of restraint and hydrogen have a larger effect on the heel-crack.
(3) A change in the rigidity of the member will change the cracking tendency, therefore rigidity of the member is a factor related to the initiation of the heel-crack. Particularly, when the vertical plate is thin, the heel-cracking tendency is increased.
(4) Even though it appears that the residual hydrogen has no effect on the heel-crack, promotion of hydrogen evolution or for hydrogen fixation will prevent the heel-crack. Thus the effect of the residual hydrogen can not be discounted in heel-cracking.
(5) The results of the test of 14 charges of 50 kg /mm^2 grade high strength steels show that semi-killed steels are less sensitive to heel-cracking than killed steels.
(6) Heel-cracks can be prevented by pre-heating or by a long bead of established lengths. The pre-heating temperature for preventing the heel-crack must be raised for steels having a higher carbon equivalent and a higher maximum underbead hardness.

5. Conclusions

In the case of 50 kg/mm^2 grade high strength steels, the heel-crack is observed after a cooling process passing the top of the ferrite area on the SH-CCT diagram. The rigidity of the member and the residual hydrogen are contributing factors to heel-cracking. The difference between heel-cracking tendcies in killed and semi-killed steels has been definitely established. While it is true that all 50 kg/mm^2 grade high strength steels are susceptible to heel-cracking, it is not known whether the heel-crack is peculiar to the 50 kg/mm^2 grade high strength steels, neither do we know the exact mechanism of the heel-crack. The heel-crack is a new type of crack in welding engineering, and further investigation will be conducted on remaining problems.

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