Varestraint Test for Hot Crack Susceptibility of HY-type High Strength Steels†

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Abstract

Hot cracking of tentative ten HY—130, nine HY—110 and three commercially used HY—90 types of base and weld metals were investigated by using the Varestraint Test (Longitudinal Varestraint Test). The hot crack susceptibilities of these steels were compared using the indices which are determined by the Varestraint Test.

Furthermore, this investigation was extended to more than forty other commercial and tentative high strength steels. The authors formulated an experimental formula to estimate the hot crack susceptibility of low nickel alloyed high strength steel, which is simply calculated from the amounts of alloyed and impure elements. As a result it was determined that amounts of carbon and nickel in steel are the most effective in a detrimental manner for the determination of the hot crack susceptibility of HY—type steel when amounts of sulphur and phosphorus in the steel are limited to less than about 0.01%, respectively.

1. Introduction

The principal advantages of HY steels are their good combination of strength and toughness and their good weldability in heavy thicknesses with little preheat and no postweld heat treatment.

Due to the above reasons HY—80 steel has been used in the welded construction for vessels under water thus far.

Recently in compliance with the demand for lighter and stronger structures, many advanced HY steels such as HY—100, HY—130, and HY—150 have been developed.

At present, early weld cracking problems which were encountered in HY—80 have been largely eliminated by adoption of proper precautions in the respective welding process. However, in the case of welding HY—100 and HY—130 in which nickel content is higher than in HY—80, weld cracking problems exist even when they were welded under the same precautions as in HY—80.

The weld cracks are, so-called, large-scale cold cracks and often seem to originate near fusion boundary as a micro hot crack, judging from microscopic investigations.

The correlation between micro-hot cracks and large-scale cold cracks is not clear at present, but it is believed the former may act as the nuclei for larger cracks that propagate at lower temperature.

Therefore, it was a resonable investigation for the authors to determine the advanced HY steels' susceptibility to hot cracking.

Thus, using the Varestraints Test[1] (Longitudinal Varestraint method), the susceptibility to hot cracking has been investigated for base and weld metals of tentative HY—130, HY—110 and commercial HY—90 type steels. Moreover, this investigation was extended to other commercial and tentative high strength steels. Finally, the authors have come up with an experimental formula to estimate the hot crack susceptibility of high strength steel, which is simply calculated from the amounts of alloyed and impure elements.

2. Testing Procedure

This investigation is composed of two experiments. Firstly, in Series I, the correlations between augmented strain and maximum crack length, L_{max}, total length of cracks, L_T, and number of cracks, N, and minimum augmented strain to cause cracking, ε_{min}, have been determined for base and weld metals with MIG and manual covered electrode of tentative HY—130, HY—110 and commercial HY—90 type steels. Then the susceptibilities to hot cracking of the tentative HY—130 and HY—110 type steels have been compared with that of commercial HY—90 steel which were safely welded under careful control of welding procedures designed to prevent large-scale cracking.

Secondly, in Series II, the effect of alloying and impure elements on hot crack susceptibility in low nickel alloyed high tension steels has been investigated using the HY type steels mentioned above and other tentative and commercial steels, the compositions of which are widely varied. As a result, an

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experimental formula which represents the susceptibility to hot cracking of low Ni alloyed steels has been determined.

2.1 Testing Apparatus and Method

The Varestraint Test[1] which is called "Longitudinal Varestraint Test" in Japan is used to determine the hot crack susceptibility of steels throughout the experiments. The device subjects a specimen to a predetermined amount of strain by applying a bending load in a longitudinal direction of welding bead while the specimen is being welded. **Figure 1** is a close-up view of the Varestraint Test apparatus at the JWRI which is similar to that described by Savage et al with the exception that it is wider.

The test method was basically the same for all experiments. The specimen was positioned in the Varestraint rig with one end rigidly clamped, the other end placed in the yoke, and attached to an air cylinder. Furthermore, in order to force the specimen to conform to the die block curvature, "bending plates" of mild steel 9 mm thick were placed on the test surface at the edge of the specimen, leaving a 25 mm wide gap in the center of the weld bead.

Welding was started at the end of the specimen nearest the yoke, and the weld bead was laid along the longitudinal axis. When the arc reached a point 20 mm from the end of the die block which was tangent to the specimen, a microswitch activated the air cylinder solenoid valve. This produced an instantaneous downward motion of the yoke to bend the specimen around the die block. The speed of the downward motion of the yoke was about 300 mm per second at air pressure of $7kg/cm^2$ in the cylinder that was measured with a high speed motion picture.

The arc was maintained past the point of loading so that interpretation of results would not be complicated due to effects of the crater.

For a given plate thickness, the applied strain (augmented strain) was varied by using die blocks of different radi. The augmented strain ε, produced in a specimen of thickness, t, bent around a die block of radius, r, and was calculated from the approximate formula; $\varepsilon \doteqdot t/2r \times 100(\%)$.

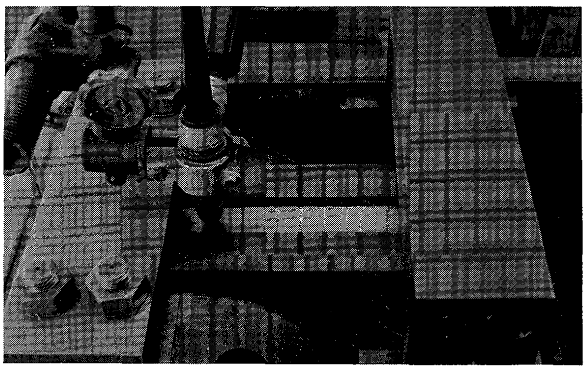


Fig. 1. Close-up view of the Varestraint Tester (Longitudinal Verestraint Tester).

Each test specimen that was machined and ground was 350mm long by 50 mm wide on the test surface, with a thickness of 12 mm with the exception of one which was 11 mm.

Two types of test specimen, that is, base and weld metals were used in this investigation as shown in **Figure 2.** Test specimens for base metal were cut and machined from 13 to 50 mm thick plates, with the length parallel to the plates primary rolling surface. Test specimens for weld metal were machined and ground from overlayed samples on the respective HY—type steel with MIG or manual covered electrode.

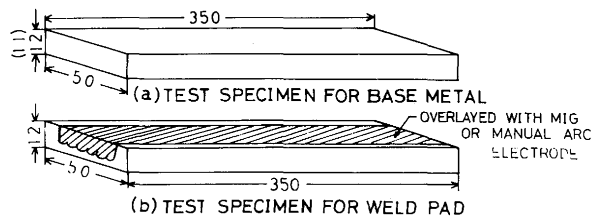


Fig. 2. Shape and dimension of test specimen used for the Varestraint Test.

2.2 Test Conditions

Details of the two series of test are shown in **Table 1.**

Table 1. Welding and Straining Conditions for the Varestraint Test.

Series	Welding Condition (TIG, DC SP)			Straining Condition
I	Ⓐ ----250A,	18—19V,	125mm/min----	0.3 to 4.0%
I	Ⓑ ----200A,	17V,	150mm/min----	0.3 to 4.0%
II	Ⓒ ----300A,	20V,	100mm/min----	4.0%

Series I test was for the purpose of determining the crack susceptibility of HY-type steels. Therefore the effects of augmented strain on cracking were investigated using two welding conditions A and B which correspond to the practical weld heat input of MIG and manual covered electrode processes, respectively. The level of augmented strain was varied from 0.3 to 4.0% for each steel, and two or three specimens were tested for each augmented strain under the same welding condition. The crack susceptibility for each steel was firstly evaluated by **CSS** index which was determined from the values of maximum length of cracks. At the same time total length of cracks, number of cracks and cracking threshold were also taken into consideration.

Series II test was for the purpose of determining the effect of elements in steel on crack susceptibility. Therefore, in this series total length of cracks on specimen surface, which was tested at 4% augmented strain under an excess weld heat input Ⓒ in order to reveal the obvious difference among various steels, was measured and compared with each other. Moreover the results of the measured total length of cracks were used for determination of an experimental formula between chemical composition and total length of cracks.

2.3 Materials Used

Chemical compositions and some mechanical properties of materials used in this experiment are tabulated in **Table 2 (a), (b), (c), (d), (e) and (f).** In Table 2 (a) experimental heats of base (A—B1～4) and weld metals with MIG (A—WM1～3) and manual covered electrode (A—WE1～3) of HY—130 type steel are tabulated. These materials were used for both Series I and II experiments. In (b) experimental heats of base and weld metals of HY—110 type steel are tabulated. The materials which are marked by * were used for only Series II, while the others are used for both. In (c) base and weld metals of commercially used HY—90 type steel are tabulated. These were also used for both. The materials tabulated in Table 2 (d), (e) and (f) are all base metals and were used for only Series II experiment. Experimental heats of HT—100 steel (2% Ni alloyed) and commercial heats of HT—80 (Q & T treated) and HT—60, HT—50 and mild steels are shown in (d), (e) and (f), respectively.

Sulphur in all the materials in Table 2 (a), (b) and (c) is reduced to less than 0.01% in order to improve on hot crack susceptibility. In the materials in (d) carbon and sulphur are consciously varied in order to investigate the effect of these elements on hot crack susceptibility under a constant nickel content of 2%.

Twenty-two different materials were used for Series I and forty-four for Series II.

3. Cracking Susceptibility of HY-type Steels

3.1 Threshold and Configuration of Cracking

The schematic appearances of crack in weld metal and HAZ of HY-type steels in this experiment are illustrated in **Figure 3.** Over than the minimum augmented strain required to cause cracking, small cracks generally originated near fusion boundaries within the weld metal as shown in Figure 3(a), and appear in the perpendicular direction to the molten ripple line at the instant augmented strain is applied. Subsequently, with an increase of augmented strain the number of cracks increased toward an inward location along the molten ripple line, and the length of cracks also generally increased. Then at high level of the augmented strain the molten ripple line was surrounded by the cracks as shown in (d). In the case of (d) the longest crack usually occured near one-third of the way inward toward the weld bead. Examples of crack appearance at 4% augmented strain are shown in **Figure 4.**

Table 2. Chemical and Mechanical Properties of Test Materials (12mmt) Used in This Experiment.

(a) HY-130 Type Steel

MARK		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Sol Al	T.S (kg/mm^2)	0.2% Y.S (kg/mm^2)	El (%)
A—B1†	Base Metal	0.08	0.28	0.46	0.003	0.005	—	5.18	0.56	0.53	0.05	—	101	97.5	23
A—B2		0.11	0.32	0.76	0.004	0.003	1.03	5.68	—	0.47	0.09	—	105.5	100.4	26
A—B3		0.09	0.26	0.50	0.007	0.006	—	5.08	0.63	0.50	0.031	0.028	99.0	96.3	24
A—B4		0.05	0.20	0.44	0.007	0.007	—	6.22	0.59	0.51	0.006	0.050	97.5	93.0	24
A—WM1	Weld Metal	0.085	0.32	1.54	0.003	0.002	0.30	3.22	0.86	0.62	—	—			
A—WM2		0.08	0.23	1.19	0.004	0.004	—	3.30	0.88	0.70	—	—			
A—WM3		0.059	0.26	1.24	0.007	0.008	—	2.48	0.90	0.83	—	—			
A—WE1		0.053	0.53	1.11	0.004	0.007	0.15	3.28	0.48	0.84	—	—			
A—WE2		0.05	0.24	1.23	0.007	0.008	—	3.44	0.94	0.50	—	—			
A—WE3		0.062	0.48	1.57	0.005	0.004	—	2.57	0.93	0.56	—	—			

(Welding Condition for Overlay)

A—WM1: 320A—26V—250mm/min, Ar+5%CO_2, 1.6 mmϕ, 2 layers-6 passes, 100°C
A—WM2: 320A—27—250mm/min, Ar+5%CO_2, 5 passes, 150°C
A—WM3: 320A—29V—300mm/min, Ar+2%O_2, 1.6 mmϕ, 1 layer
} MIG

A—WE1: 170A—25V—160mm/min, 2 layers-10 passes, 100°C
A—WE2: 170A—24V—145mm/min, 7 passes, 150°C
A—WE3: 170A—23V—150mm/min, 4 mmϕ, 4 layers
} Manual Covered Electrode

† Thickness of Testing Plate is 11mm

(b) HY—110 Type Steel

MARK		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	O (ppm)	T.S. (kg/mm²)	0.2%Y.S. (kg/mm²)	El (%)
B—B1	Base Metal	0.065	0.20	0.50	0.004	0.006	—	4.07	0.55	0.52	0.06	30	90.0	82.0	24.8
B—B2		0.11	0.22	0.75	0.004	0.005	—	3.33	0.80	0.44	0.04	30	93.0	89.3	23.2
B—B3		0.11	0.26	0.70	0.007	0.007	—	3.47	0.70	0.53	0.017	(Sol. Al 0.052)	88.5	83.0	25
B—B4*≑		0.070	0.50	0.50	0.003	0.006	—	4.14	0.53	0.50	0.06	60	92.0	89.4	23.4
B—B5*≑		0.094	0.30	0.60	0.003	0.006	—	3.30	0.78	0.40	0.07	60	99.0	96.1	24.2
B—WM1	Weld Metal	0.068	0.32	1.28	0.001	0.002	0.27	2.66	0.52	0.49					
B—WM2		0.071	0.26	1.43	0.003	0.004	0.38	2.50	0.85	0.70					
B—WM3		0.065	0.25	1.30	0.003	0.007	—	2.65	0.53	0.61					
B—WM4*		0.076	0.36	1.69	0.003	0.002	0.25	2.24	0.75	0.56					
B—WM5*		0.069	0.37	1.38	0.002	0.002	0.25	2.31	0.09	0.47					
B—WM6*		0.063	0.36	1.37	0.002	0.002	0.32	2.31	0.52	0.47					
B—WM7*		0.076	0.36	1.70	0.002	0.003	0.29	2.24	0.52	0.46					
B—WM8*		0.075	0.38	1.76	0.001	0.003	0.24	1.93	0.51	0.64					
B—WM9*		0.063	0.37	1.73	0.001	0.002	0.23	2.28	0.52	0.50					
B—WM10*		0.065	0.37	1.65	0.002	0.002	0.24	2.23	0.12	0.48					
B—WE1		0.05	0.47	1.10	0.003	0.004	0.04	2.67	0.76	0.35					
B—WE2		0.057	0.40	1.64	0.007	0.004	—	2.37	0.84	0.50					
B—WE3		0.041	0.42	1.33	0.009	0.009	—	2.40	0.87	0.61					

(Welding Condition for Overlay)
B—WM1: 300A—25V—220mm/min, Ar+5%CO_2, 1.6 mmϕ, 2 layers-7 passes, 100°C
B—WM2: 340A—27V—280mm/min, Ar+5%CO_2, 1.6 mmϕ, 4 layers-12 passes, 150°C } MIG
B—WM3: 240A—27V—200mm/min, 1.2 mmϕ, 3 layers-24 passes, 150°C
B—WM4～B—WM10: Same as B—WM1
B—WE1: 180A—25V—150mm/min, 2 layers-9 passes
B—WE2: 170A—24V—150mm/min, 4 mmϕ, 4 layers-16 passes, 150°C } Manual Covered Electrode
B—WE3: 170A—23V—150mm/min, 4 mmϕ, 4 layers-41 passes
* Tested only in Welding Condition ©
≑ Vacuum Melted

(c) HY—90 Type Steel

MARK		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	O	T.S. (kg/mm²)	0.2%Y.S. (kg/mm²)	El. (%)
C—BI	Base Metal	0.10	0.24	0.58	0.008	0.006	—	2.60	0.47	0.38	—	—	74.0	69.0	31.0
C—WM1	Weld Metal	0.05	0.24	0.90	0.008	0.008	—	3.18	0.18	0.44	—	—			
C—WE1		0.048	0.45	0.98	0.011	0.009	0.03	2.78	—	0.33	—	—			

(Welding Condition for Overlay)
C—WM1: 260A—29V—200mm/min, Ar+2%O_2, 1.2 mmϕ, 2 layers————MIG
C—WE1: 180A—25V—150mm/min, 2 layers-9 passes—— Manual Covered Electrode

(d) HT—100 Steel (2% Ni Alloy)

MARK		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Sol Al	T.S (kg/mm²)	Y.S. (kg/mm²)	El. (%)
D—B1*	Base Metal	0.10	0.30	0.79	0.003	0.005	<0.01	2.01	0.56	0.55	0.06	0.07	103.5	97.3	17.5
D—B2*		0.10	0.27	0.83	0.006	0.010	0.03	2.01	0.55	0.55	0.06	0.07	104.0	98.6	17.5
D—B3*		0.10	0.23	0.81	0.007	0.017	0.03	1.93	0.53	0.54	0.06	0.07	104.4	99.7	15.5
D—B4*		0.14	0.27	0.45	0.007	0.019	0.03	1.98	0.57	0.54	0.06	0.07	109.7	105.3	16.5
D—B5*		0.13	0.21	0.73	0.003	0.005	<0.01	1.97	0.54	0.54	0.06	0.07	107.0	102.3	17.0
D—B6*		0.14	0.24	0.79	0.007	0.010	0.03	1.95	0.54	0.54	0.06	0.07	101.0	97.7	14.5
D—B7*		0.15	0.29	0.81	0.007	0.020	0.03	2.00	0.57	0.54	0.06	0.07	105.6	100.5	15.5
D—B8*		0.14	0.27	0.83	0.006	0.035	0.03	1.98	0.54	0.55	0.06	0.07	105.3	100.8	15.0
D—B9*		0.19	0.28	0.84	0.007	0.036	0.03	1.98	0.58	0.55	0.06	0.07	106.5	101.3	12.0

Heat Treatment
D—B1～D—B3: 900°C×1 hr., W.Q.→600°C×1 hr, A.C.
D—B4～D—B8: 900°C×1 hr., W.Q.→630°C×1 hr, A.C.
D—B9 : 900°C×1 hr., W.Q.→650°C×1 hr, A.C.

(e) HT—80 Steel

MARK		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	T.S. (kg/mm^2)	0.2%Y.S (kg/mm^2)	El (%)
E—B1*	Base Metal	0.091	0.30	0.89	0.001	0.004	0.23	1.04	0.59	0.40	0.04	86	82	22
E—B2*		0.096	0.30	0.77	0.005	0.005	0.25	1.16	0.38	0.44	0.025	83.2	77.5	26
E—B3*		0.15	0.27	0.88	0.015	0.004	0.28	0.016	0.52	0.36	0.031	—	—	—

(f) HT—60, HT—50, & Mild (SS—41) Steels

MARK		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	O
F—B1*	HT—60	0.20	0.43	1.45	0.013	0.012	0.010	0.01	0.008	tr	0.008	—
G—B1*	HT—50	0.16	0.49	1.39	0.016	0.008	—	tr	0.007	0.01	—	30ppm
H—B1*	SS—41	0.16	0.03	0.98	0.014	0.016						

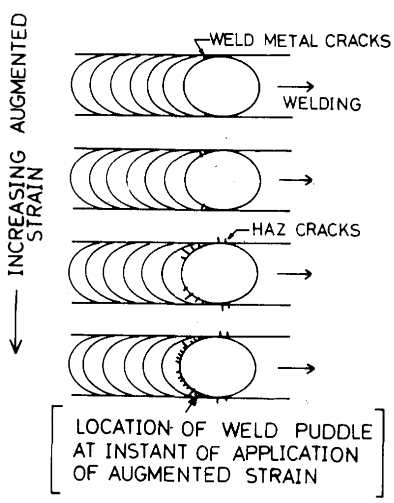


Fig. 3. Schematic appearance of the variation of the crack in weld and HAZ with an increase of augmented strain.

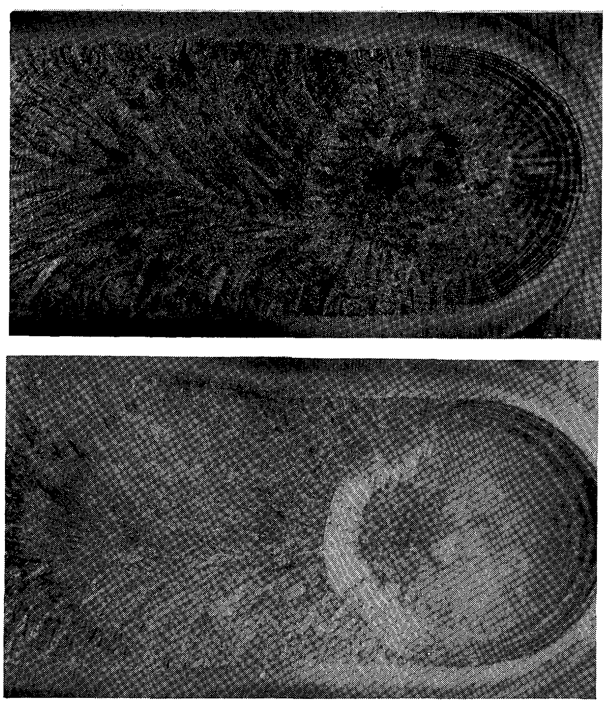


Fig. 4. Example of crack appearance at 4% augmented strain.
(a) HY—130 type A—B3 base metal
(b) HY—110 type B—B1 base metal

The occurrence of crack in HAZ near fusion boundaries depended strongly on material, that is, some occurred at level of augmented strain (a) or (b) in Figure 3, while some did not occur even at (d).

The cracking threshold for each base and weld metals, that is, the minimum augmented strain required to cause cracking is shown in **Figure 5** on an average of two or three specimens. Black and white arrows indicated the cracking threshold for the weld metal and HAZ, respectively, over which cracking occurs. In the case of A—WM3 weld metal, the crack threshold could not be decided because some inclusions like weld slag were opened in low level augmented strain.

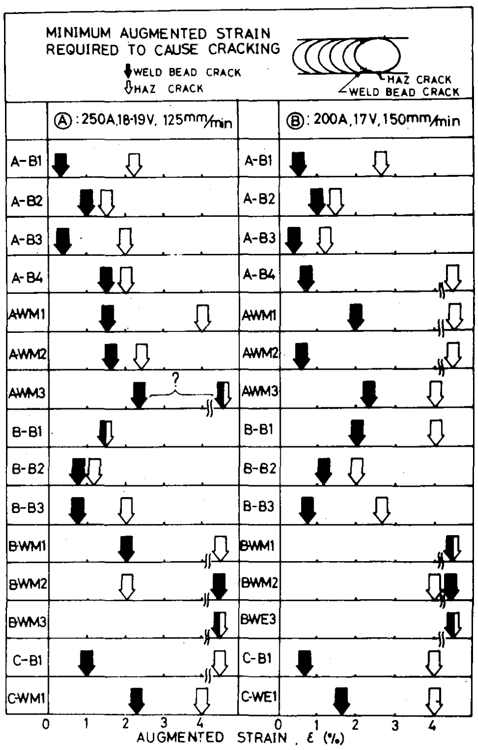


Fig. 5. Cracking threshold for each base and weld metals.

As a result susceptibility to hot cracking in TIG arc melted zone of base and weld metals was generally worse than that in HAZ in which crack was not often seen even at 4% strain level. Moreover, the crack susceptibility of TIG arc melted zone of base metal was worse than that of both weld metals which were overlayed with MIG and manual arc welding processes using the respective strength electrode.

3.2 Maximum crack length and CSS index

One of the authors proposed from the result of Transverse Varestraint Test[2] that the indices of **CST** and **CSS** represent the reasonable solidification crack susceptibilities for alloy, that is, the higher the value of **CTS** or **CSS** of alloy, the better the solidification crack susceptibility.

The **CST** and the **CSS** show the critical values of strain rate for temperature drop and time during weld solidification of alloy, respectively, in which solidification crack occurred in longitudinal direction of weld bead.

The above indices were determined using the relationship between augmented strain and length of the longest crack. In the Transverse Varestraint Test, the longest crack usually occurred near the weld center line. Therefore, the length of the longest crack was easy to convert into temperature range, that is, Brittleness Temperature Range, from the results of temperature measurement, or passing time of heat source over the crack which is divided by welding speed.

However in the Longitudinal Varestraint Test, the longest crack did not occur as mentioned previously. Therefore the value of **CST** in Longitudinal Varestraint Test was usualy difficult to determine because measurement of temperature distribution along the longest crack was practically impossible.

However, the value of **CSS** in Longitudinal Varestraint Test was easily determined for a given welding condition. This value of **CSS** is useful for a relative comparison of hot crack susceptibility of steels. The value of **CSS** in Longitudinal Varestraint Test was decided by the relation between length of the longest crack (maximum crack length) and augmented strain. The schematic illustration is shown in **Figure 6.** Each location within the weld metal and boundaries have individual curve for the maximum crack length for variation of augmented strain. Therefore the value of **CSS** (%/sec) was calculated by $v \times \tan\theta$, where $\tan\theta$ was determined by the inclination of the tangential line to the most rising cracking curve (%/cm) and v was welding speed (cm/sec). This value represents the critical value for strain rate to time required to cause cracking during weld solidification of alloy, below which any crack did not occur in the welds.

The values of **CSS** index were determined for all HY-type base and weld metals used. Some examples are shown in **Figure 7 (a)** through **(h).** **(CSS)**$_{Ⓐ}$ and

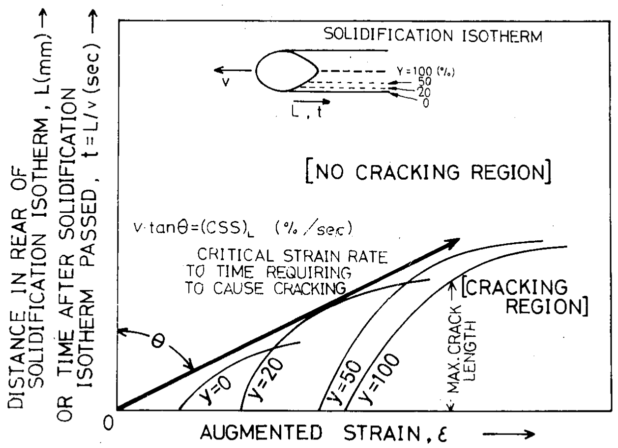
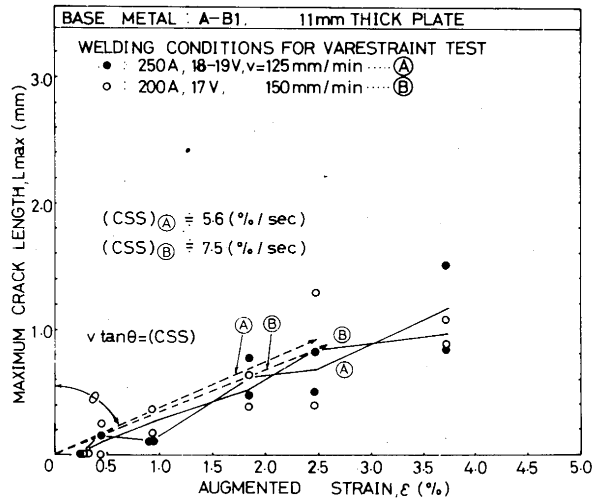
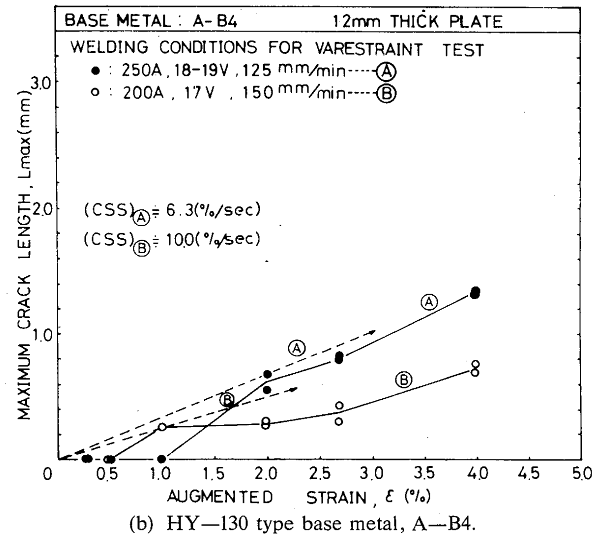


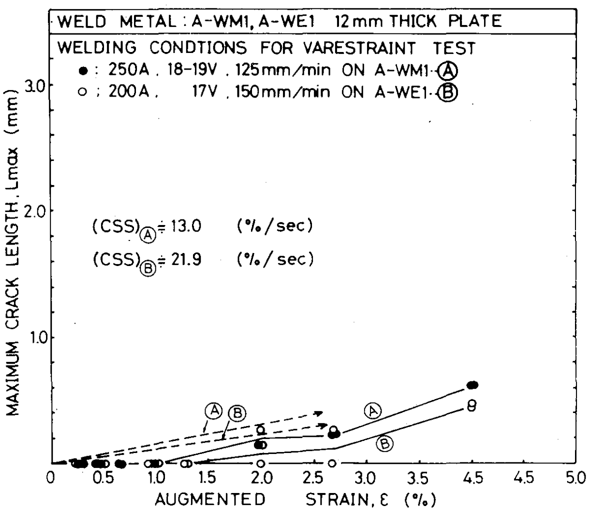
Fig. 6. Illustration of CSS index in Longitudinal Varestraint Test.



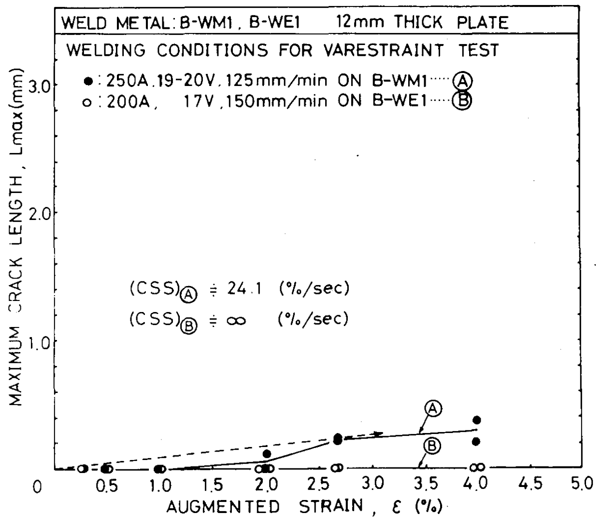
(a) HY—130 type base metal, A—B1.



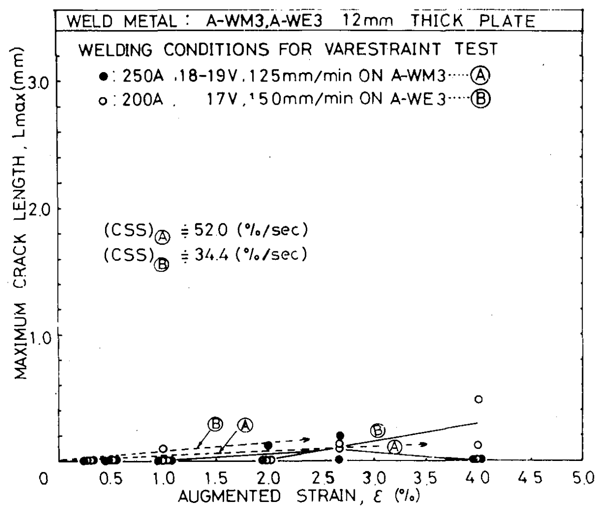
(b) HY—130 type base metal, A—B4.



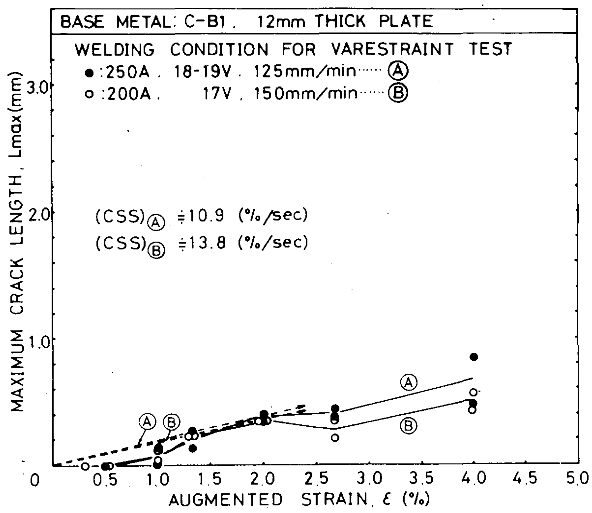
(c) HY—130 type weld metals, A—WM1 & A—WE1



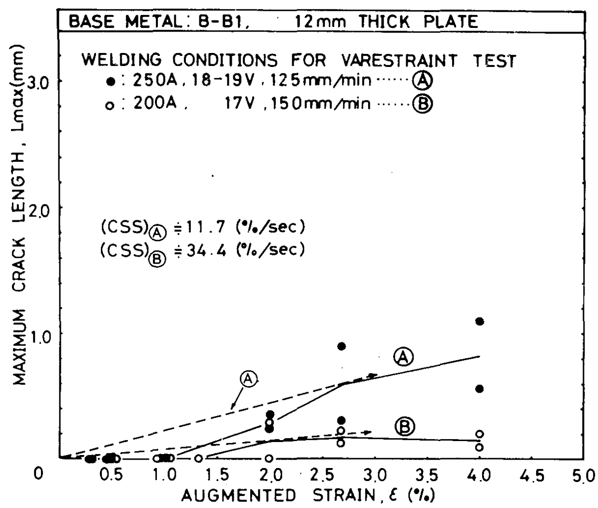
(f) HY—110 type weld metals, B—WM1 & B—WE1



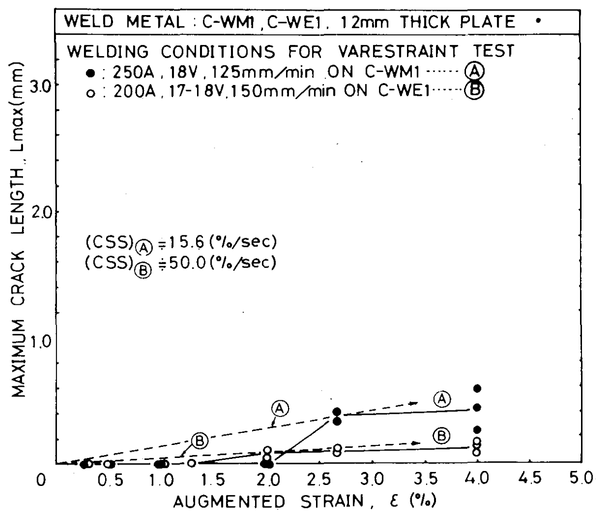
(d) HY—130 type weld metals, A—WM3 & A—WE3



(g) HY—90 type base metal, C—B1



(e) HY—110 type base metal, B—B1



(h) HY—90 type weld metals, C—WM1 & C—WE1

Fig. 7. Examples of relations between maximum crack length and augmented strain.

Table 3. Values of Index CSS (%/sec) for Welding Conditions Ⓐ and Ⓑ

Material		Condition Ⓐ	Condition Ⓑ
HY—130 Type Steel	A—B1	5.6	7.5
	A—B2	7.3	10.6
	A—B3	2.5	6.3
	A—B4	6.3	10.0
	A—WM1	13.0	—
	A—WM2	19.8	—
	A—WM3	52.0	—
	A—WE1	—	21.9
	A—WE2	—	Not Decided
	A—WE3	—	34.4
HY—110 Type Steel	B—B1	11.6	34.4
	B—B2	7.8	14.1
	B—B3	5.2	18.8
	B—WM1	24.1	—
	B—WM2	83.3	—
	B—WM3	∞	—
	B—WE1	—	∞
	B—WE2	—	100
	B—WE3	—	∞
HY—90 Type Steel	C—B1	10.9	13.8
	C—WM1	15.6	—
	C—WE1	—	50.0

$(CSS)_{Ⓑ}$ show the values of **CSS** at welding conditions Ⓐ and Ⓑ, respectively. The value of **CSS** was defined as infinite when no crack was seen at strain level of 4%. In **Table 3** the values of **CSS** for welding conditions Ⓐ and Ⓑ were collectively tabulated for all HY—type base and weld metals used in this investigation.

From the result in Table 3 it was clear that the **CSS** values of base metals are generally smaller than those of weld metals of the same level in strength, that is, the TIG arc melted zone of the base metal is very susceptible to hot cracking during welding than the respective weld metal. It was therefore considered, that the hot crack will usually originate in the so-called "Unmixed Zone"[3] or "Transition Zone" near fusion boundaries in the actual welded joint but in the composite weld metal, when the strain is more than the **CSS** value of the material and is burdened in the welded joint during weld solidification.

3.3 Total Length of Cracks

Most papers[4), 5), 6)] concerning the Varestraint Test have treated total length of cracks as one of the most important index for evaluation of hot crack susceptibility of steels. Therefore in this investigation total length of cracks, L_T, was also measured for all specimens tested. **Figure 8 (a)** and **(b)** show the relations between L_T and augmented strain for base and MIG weld metals in case of welding condition Ⓐ. In Figure 8 (a) the results of HY—80 and HY—130/150 by Thompson[5] are also compared, though welding condition for the test was slightly different.

In HY—130 type steels A—B1, A—B2 and A—B4 show a similar tendency to Thompson's HY—130/150 steel in case of low level of augmented strain up to about 3%, while A—B4 is different from the others in higher level of the strain. A—B3 was always the highest in L_T among these four HY—130 type steels.

B—B1 in HY—110 type steels showed the lowest L_T among the three steels, and was lower than C—B1 of HY—90 type steel which is used commercially.

Concerning MIG arc weld metals in Figure 8 (b) very little crack was observed in A—WM3, B—WM2 and B—WM3 even at 4% strain level. Moreover the other weld metals also showed lower crack susceptibility than the base metals in Figure 8 (a).

3.4 Number of Cracks

Figures 9 (a) and **(b)** show the number of cracks after the Varestraint Test was made against augmented strain in welding condition Ⓐ for base and MIG weld metals, respectively. These tendencies in Figures 9 (a) and (b) are similar to the results in Figure 8 (a) and (b).

As a result, base metals B—BI (HY—110 type) and C—BI (HY—90 type) are considered to be the best in hot crack susceptibility within the base metals tested in this investigation and the hot crack susceptibility in the unmixed zones in the case of actual welded joint would be considered to be equivalent to the weld metals.

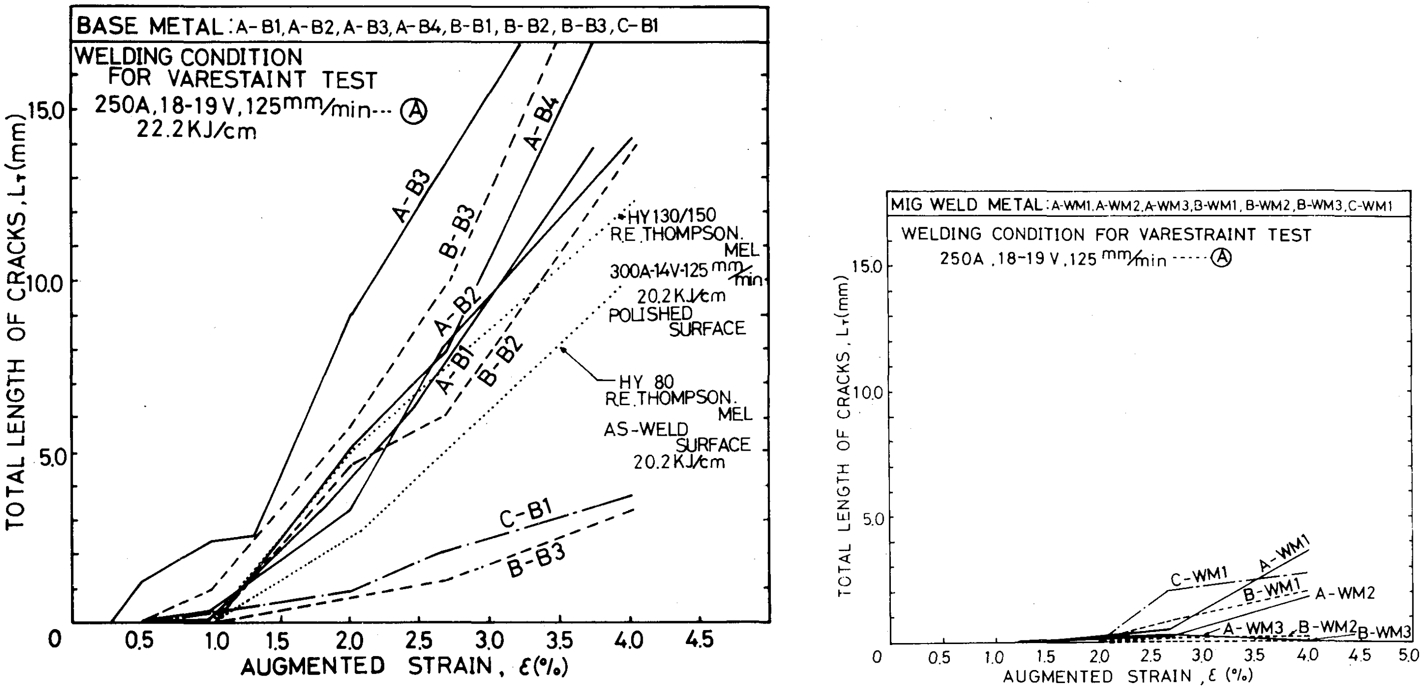
4. Effect of Chemical Composition on Hot Crack Susceptibility

4.1 Total Length of Cracks as An Index Evaluating Hot Crack Susceptibility

As mentioned above, the value of **CSS** was determined as a result of the Varestraint Test for many specimens which were tested in variation of augmented strain. Therefore the measurement for the value of **CSS** for many steels is usually troublesome, and moreover it is difficult to obtain such large quantity of steel when the steel is made on trial condition.

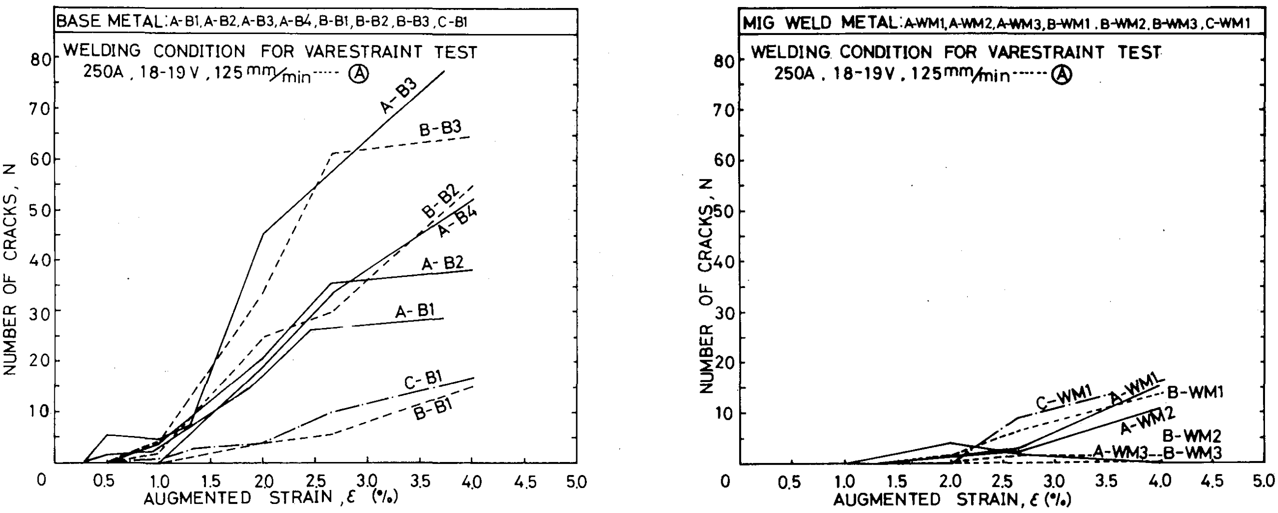
Therefore, for the purpose of doing a quick judgment for hot crack susceptibility of steel it was expected to have another simple index.

Now, the authors tried to have the relation between the value of **CSS** of HY—type steels in Series I and maximum crack length at 4% strain, L_{max}, total



(a) Base metals for welding condition Ⓐ (b) MIG weld metals for welding condition Ⓐ.

Fig. 8. Examples of relations between total length of cracks and augmented strain.



(a) Base metals for welding condition Ⓐ. (b) MIG weld metals for welding condition Ⓐ.

Fig. 9. Examples of relations between number of cracks and augmented strain.

length of cracks at 4% strain, L_T, number of cracks at 4% strain, N, or augmented strain required to cause cracking, ε_{min}. The relations are collectively shown in **Figure 10** in which black and white circles show the data obtained by welding conditions Ⓐ and Ⓑ, respectively.

ε_{min} and N are scattered considerably against **CSS.** However, L_{max} and L_T have a good relations. It means that the value of **CSS** in HY-type steel can be easily estimated by measuring L_{max} or L_T. Of the two indices, the authors think that L_T is superior to L_{max} because it is much sharper in relation and less scattering in the data measured.

That is to say, total length of cracks at 4% augmented strain, L_T, is also a prominent index to evaluate hot crack susceptibility of steel which is a substitute for **CSS.**

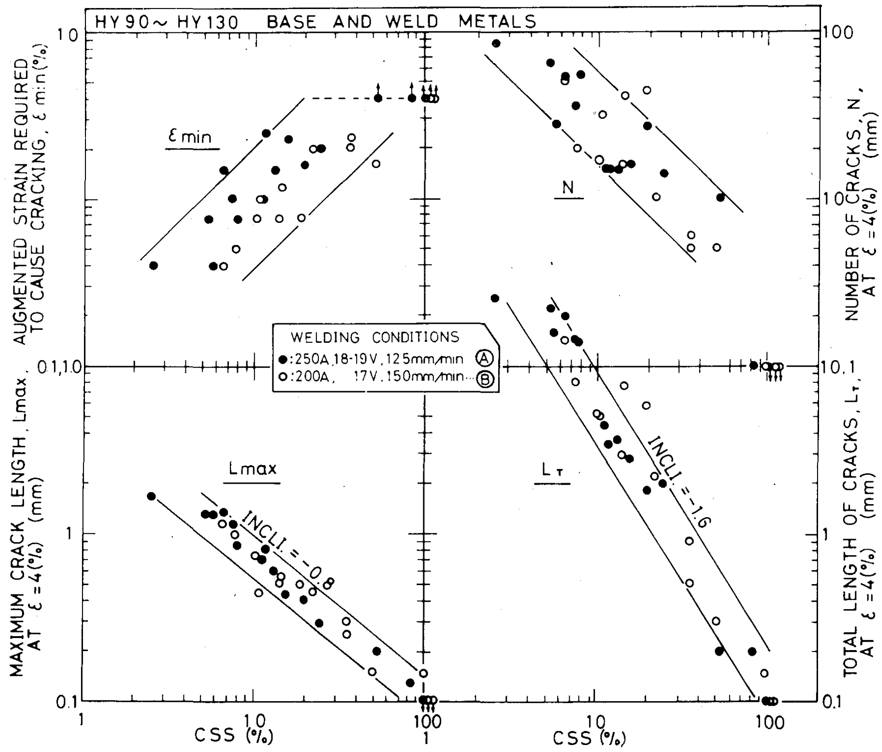


Fig. 10. The relations between CSS index and ε_{min}, N, L_{max}, and L_T at 4% augmented strain.

4.2 *Relation between Chemical Composition and Hot Crack Susceptibility of Steel*

More than 40 kinds of steel including HY-type steels described above were tested as Series II using welding condition Ⓒ, that is, 300A, 100mm/min, 20V and augmented strain level of 4%.

Total length of cracks, L_T, for each steel is tabulated in **Table 4.** Each L_T shows a mean value of two to four specimens. The L_T in A—B1 steel was shown for the result of about 3.7% strain level on 11 mm thick plates.

Next, using all the data obtained, the authors have determined an experimental formula to evaluate hot crack susceptibility on these steels by means of the method of least squares, in relation between chemical composition and L_T.

By calculation of an experimental formula

Table 4. Values of Total Length of Cracks (L_T) (mm) at Augmented Strain of 4% for Welding Condition Ⓒ.

Material	L_T(mm) (ε=4%)	Material	L_T(mm) (ε=4%)	Material	L_T(mm) (ε=4%)
A—B1	17.5	B—WM4	0.2	D—B4	12.3
A—B3	23.5	B—WM5	0	D—B5	10.2
A—B4	23.5	B—WM6	0	D—B6	13.7
A—WM1	5.7	B—WM7	0.1	D—B7	12.8
A—WM2	5.5	B—WM8	0	D—B8	13.3
A—WM3	0.7	B—WM9	0.1	D—B9	20.7
A—WE1	0	B—WM10	0.4	E—B1	0.7
A—WE3	0.3	B—WE1	0	E—B2	0.7
B—B1	10.5	B—WE2	0	E—B3	4.2
B—B2	20.0	B—WE3	0.5	F—B1	7.8
B—B3	23.7	C—B1	7.6	G—B1	1.5
B—B4	14.3	C—WM1	0.4	H—B1	7.3
B—B5	13.0	C—WE1	0.3		
B—WM1	0.1	D—B1	8.2		
B—WM2	0.1	D—B2	6.3		
B—WM3	0	D—B3	11.4		

chemical compositions in those steels were determined to be carbon, silicon, manganese, phosphorus, sulphur and nickel. As the effects of chromium[6), 7)] and vanadium[7)] on hot crack susceptibility were considered to be minor in comparison to other compositions in high tension steels, they were neglected.

The formula obtained is given by

$$L_T \doteqdot 91\left\{[\%C]-\frac{1}{8}[\%Si]-\frac{1}{15}[\%Mn]+\frac{1}{2}[\%S]+\frac{1}{26}[\%Ni]\right\}(mm) \qquad (1)$$

where, L_T is total length of cracks in weld metal and HAZ for welding condition, 300A, 100mm/min, 20V and 4% augmented strain. [%C], [%Si], [%Mn], [%S] and [%Ni] are weight percentage of C, Si, Mn, S and Ni, respectively.

Fomula (1) is reliable for the steels within C: 0.04, to 0.20%, Si: 0.03 to 0.53%, Mn: 0.44 to 1.76%, P: <0.016%, S: <0.036%, Cu: <0.38%, Ni: <6.22%, Cr: <0.94%, M_0: <0.84% and V: <0.09%.

The term of P in the formula was eliminated because the effect was so small in the coefficient of P.

However, in HY-type steels for commercial use the sulphur content is usually less than 0.02% and mostly up to 0.01% as shown in Table 2 (a), (b) and (c). Therefore, the authors have again calculated the formula using all the steels except D—B8 and D—B9 which have high sulphur constents. The results is given by

$$L_T \doteqdot 91\left\{[\%C]-\frac{1}{9}[\%Si]-\frac{1}{15}[\%Mn]+\frac{1}{26}[\%Ni]\right\}\pm 3.0(mm) \qquad (2)$$

Formula (2) is reliable for the steels in Formula (1) with the exception of sulphur, which is less than 0.02%.

In Formula (2) the effect of sulphur was too small in comparison with other compositions to calculate the coefficient. That is to say, in the steels in which sulphur and phosphorus are low level and less than 0.02%, and mostly less than 0.01%, it is considered that obvious detrimental effects of those compositions are no longer detected.

Judging from the amounts of chemical compositions in Table 2, it is considered that C and Ni show the most powerful effect in detrimental fashion on L_T in Formulas (1) and (2). Si and Mn show beneficial effect on L_T while the degree of effectiveness is lower than that of Ni and C.

Several investigations[7~10)] have so far shown that quantitative expressions can be developed to relate hot crack susceptibility to chemical compositions. In these expressions the coefficient of Ni to C shows different value with each other. The coefficient of Ni in this investigation is expressed by 1/26. When the tendency of C and Ni to form austenite on solidification is assessed on the basis of the peritectic composition, the potency of Ni to C was calculated as 1/25[8)] and 1/28[11)]. Therefore it is considered that the hot crack susceptibility in HY—type steel strongly depends on the potency to form austenite on solidification. As Mn has a dual role, that is, the effects of immobilizing the sulphur as MnS and of stabilizing the austenite, it is considered that the coefficient of Mn showed −1/15 in this investigation.

As mentioned above the amounts of C and Ni compositions mainly governed the hot crack susceptibility of HY—type steels in this investigation. Therefore, L_T is plotted in the co-ordinates of C and Ni in steel as shown in **Figure 11.**

Three solid lines show the equi-total length of cracks of $L_T \approx$ 1.0, 10 and 20mm, respectively. Moreover, four different zones (I), (II), (III) and (IV), which are divided by three broken lines, show the variation of the solidification modes at peritectic temperature, which are illustrated in the right hand of Figure 11. These broken lines are approximately drawn by the straight lines between the respective points in Fe-C and Fe-Ni binary diagrams, which could be predicted from the result by Buckley[12)].

From the result in Figure 11 the steels whose compositions are located in zones (I) and (II), are mostly solidified in δ phase, and are insusceptible to hot cracking. The steels in zone (III) rapidly increase hot crack susceptibility with an increase of C and Ni contents. Moreover, detrimental effect of S is obvious in 0.15—0.16%C in nickelles steel and 0.10%C in 2% nickel steel, but not obvious in more than 0.15%C in 2% nickel steel. Therefore it is recommended that S content in HY-type steel is desirable for less than 0.01%.

Concerning the development of HY-type steels in the future, in view of hot crack susceptibility C should be decreased with an increase of Ni under the low level of S and P of less than 0.01%.

5. Conclusions

(1) The susceptibility to hot crack for TIG arc melted zone in base metal of HY-type steels is usually inferior to that for the respective weld metals with MIG and manual convered electrode. Therefore, it is considered that hot crack will be originated at the so-called unmixed or transition zone near fusion boundaries in practical welded joint of HY-

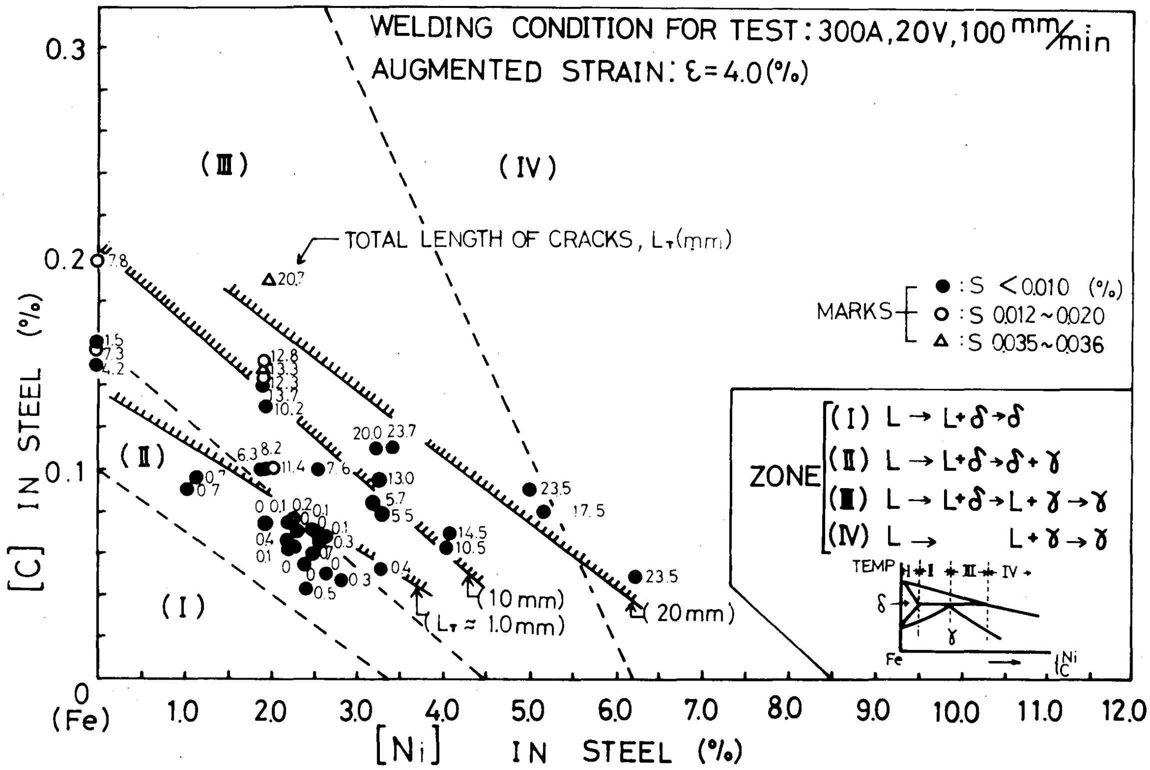


Fig. 11. Diagrammatic representation of equi-total length of cracks at 4% augmented strain in relation to C and Ni in steel.

type steel. Moreover the higher the strength in HY-type steel, the worse the susceptibility to hot crack in general.

(2) In this investigation, however, a HY—110 type steel, B—B1, whose susceptibility is comparable or superior to commercial HY—90 type steel has been obtained. The crack susceptibility in relation to this base metal is also comparable to the respective weld metals with MIG and manual covered electrode.

(3) In the Varestraint Test total length of cracks at 4% augmented strain was one of the most reliable index to investigate easily susceptible to hot crack of HY-type steel, though the value of **CSS** (critical strain rate to time to cause cracking) is theoretically the most important index.
There was a good correlation between **CSS** value and total length of cracks at 4% augmented strain.

(4) The hot crack susceptibility was compared for base and weld metals of more than forty steels, using the index of total length of cracks at 4% augmented strain and TIG arc welding condition of 300A, 100mm/min, 20V. Then an experimental formura for determination of the hot crack susceptibility for HY-type steel whose S and P contents are less than 0.02% and 0.016%, respectively, is given by

$$L_T \doteqdot 91\left\{[\%C] - \frac{1}{9}[\%Si] - \frac{1}{15}[\%Mn] + \frac{1}{26}[\%Ni]\right\} \pm 3.0\ (mm)$$

where, L_T is total length of cracks.
[%C], for example, is weight percentage of carbon in steel. The above formula is reliable for the steels within C: 0.04 to 0.20%, Si: 0.03 to 0.53%, Mn: 0.44 to 1.76%, P: <0.016%, S: <0.02%, Cu: <0.38%, Ni: <6.22%, Cr: <0.94%, Mo: <0.84% and V: <0.09%.
As a result, C and Ni showed the most powerful detrimental effects in HY-type steel. Si and Mn showed benefitial effects. However the effect of S and P was neglected in comparison to of other elements because they were too small to calculate.

(5) The tendency in variation of hot crack susceptibility for various HY-type steels was well explained with the difference of solidification mode in Fe-Ni-C ternary diagram. That is, the steels within the range of δ phase solidification were insusceptible to hot cracking, but with an increase γ phase in solidification the steels showed much susceptibility to hot cracking. Therefore, it is concluded that the composition of HY-type steel should be carefully controlled, that is, C should

be decreased with an increase of Ni even if S and P are low enough or less than 0.01%.

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