Brittle Fracture Strength of Welded Joints

The brittle fracture initiation characteristics of welded joints for various high strength steels are studied after welding is carried out with various heat inputs

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ABSTRACT. In the majority of brittle fracture casualities in welded structures it has been reported that the fracture initiated at a pre-existing or elongated weld defect or crack along the bond or in the weld metal rather than in the base metal. Sometimes the brittle fracture is influenced by the superposition of welding residual stress.

This paper describes the results of studies of the brittle fracture initiation characteristics of welded joints for various high strength steels including 80 and 100 kg/mm² high strength steels and the low temperature structural steels including 9% Ni steel. These were welded with various heat inputs and were evaluated by using the deep notch test specimens with welded joints. The heat input control is needed not for HT60 but for HT80.

In addition, the effect of super-imposition of residual stress on the increase in brittle fracture initiation temperature for various high strength steels was investigated theoretically by means of fracture mechanics concept.

Finally, the characteristics of the brittle crack path in the region of the welded joint for various kinds of steel were observed. The brittle crack propagates along the welded joint when the weld metal is deposited by submerged-arc welding, or the applied stress is large for HT80.

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Paper presented at the AWS 50th Annual Meeting held in Philadelphia, Pa., during April 28th to May 2, 1969.

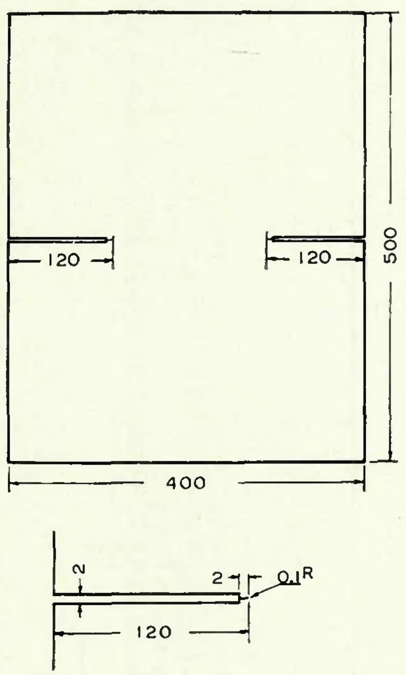


Fig. 1—Deep notch test specimen and details of notch

Introduction

To prevent brittle fracture in welded structures, it is necessary to use steels and electrodes which are suitable to their service conditions and to adopt suitable welding conditions or heat input.

In general, a notch is needed for the initiation of brittle fracture. Practically, weld cracks or defects are found as the notches along the bond or in the weld metal. Meanwhile, accompanying the automation of welding, heat input has been increasing from a viewpoint of improving productivity. However, the effect of heat input on the decrease in ductility of the welded joint for high strength steels has recently been receiving especial attention.

The brittle fracture initiation characteristics of welded joints with notch can be evaluated by using the deep notch test specimens with welded joints as well as the plane deep notch test specimen for the base metal as introduced previously.[1]

The brittle fracture initiation temperature increases by superimposition of welding residual stress.

The brittle crack paths in the region of welded joint deposited by the shielded-arc and the submerged-arc weldings for various high strength steels differ from those obtained with the shielded-arc welding of mild steel.

Brittle Facture Initiation Characteristics of Welded Joints

Deep Notch Test

The brittle fracture initiation characteristics of base metal in which a notch exists can be evaluated by using the deep notch test specimens as described previously.[1]

The deep notch test specimen used

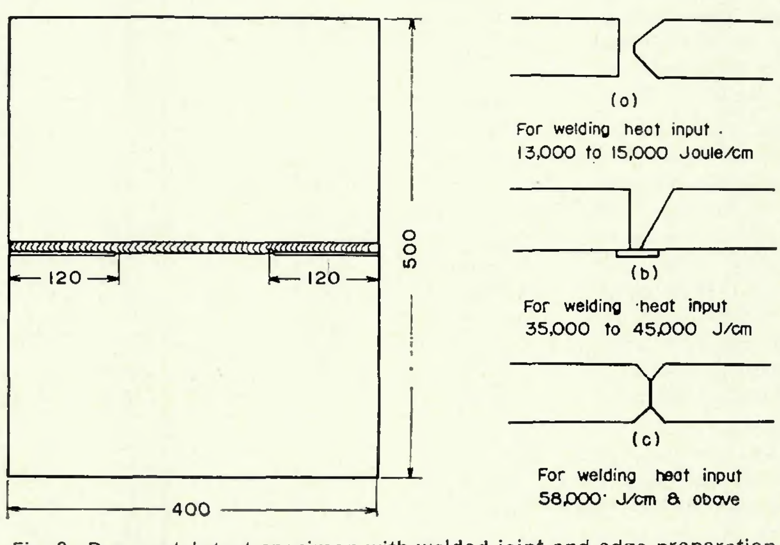


Fig. 2—Deep notch test specimen with welded joint and edge preparation

for the evaluation of base metal is shown in Fig. 1. The specimen has a size of 500 mm × 400 mm, and the notch length is either 80 mm or 120 mm. The notch has a sharp tip of 0.1 mm radius, 0.2 mm wide and 2 mm long, and it was demonstrated previously that the radius is equivalent to a natural crack from the viewpoint of brittle fracture initiation characteristics.

The welded deep notch test specimen used for the evaluation of brittle fracture initiation characteristics of the bond and the weld metal is shown in Fig. 2. Likewise shown are the edge preparations of test specimen for the bond in the case of manual welding with a heat input of 13,000 joules/cm; the automatic welding or the submerged-arc welding, 35,000 joules/cm; and the automatic welding, 58,000 joules/cm, respectively. The edge preparations of test specimen for investigating the weld metal are, however, V or X types. The reinforcement of welded bead in the test specimen is machined off. The residual stress along the welded joint in the direction normal to the welded joint is, generally, as low as several kg/mm² as in the welded condition. Therefore, the residual stress can be negligible in comparison with the net stress at fracture, and the brittle fracture initiation characteristics of the bond or the weld metal without the residual stress can be evaluated by using this type specimen.

The test specimen was welded to the pull plate and pulled in tension in a large structural testing machine or a test rig. The specimen was cooled with liquid nitrogen, and the temperature was measured with thermocouples.

For the condition of brittle fracture initiation in the temperature region where the brittle fracture initiates at low stress levels, the following modified Griffith-Orowan energy equation for the finite breadth specimen is applied:[1]

$$\left.\begin{aligned} &\frac{\pi[f(\gamma)\sigma]^2 c}{E} = 2S_i \\ &f(\gamma) = \sqrt{\frac{2}{\pi\sigma}\left(\tan\frac{\pi\sigma}{2} + 0.1\sin\pi\gamma\right)},\ \gamma = c/b. \end{aligned}\right\} \quad (1)$$

where, σ = stress, c = notch length, E = Young's modulus, b = half breadth of specimen, S_i = plastic surface energy or work done required for creating new surfaces per unit area.

There is a linear relationship between logarithm of S_i and the reciprocal of the absolute temperature, T_k, and can be expressed by the

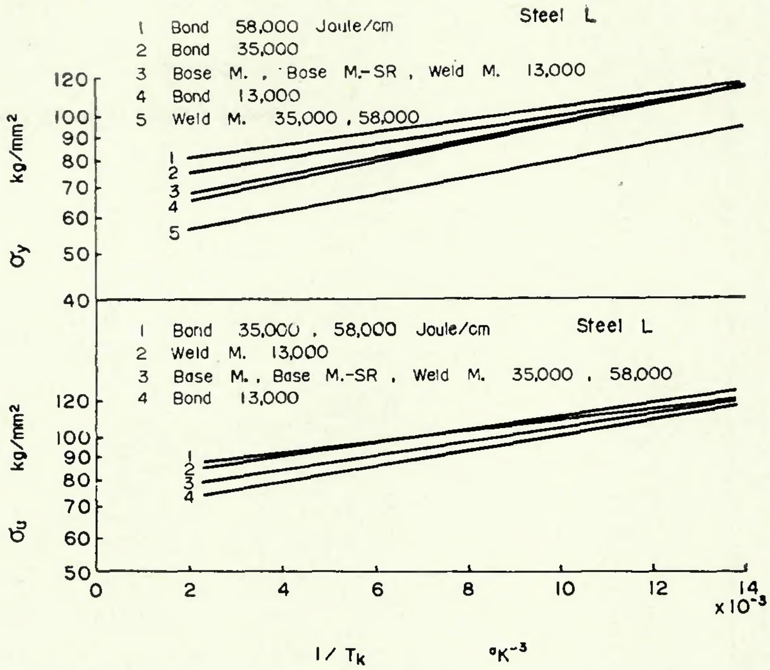


Fig. 3—Correlation between yield stress, tensile strength and reciprocal of absolute temperature (steel L)

following equation:

$$S_i = S_{oi}e^{-2k_i/T_k} \quad (2)$$

where S_{oi} and k_i are the material constants, and can be determined from, for example, the straight lines in Fig. 6.

The linear relationship may be valid up to the temperature of general yielding, where the net stress on notch section is equal to the yield stress at temperature concerned.

On the other hand, the logarithm of the yield stress σ_y is linearly related to the reciprocal of the absolute temperature T_k as follows:

$$\sigma_y = \sigma_{oy}\, e^{k_y/T_k} \quad (3)$$

where, σ_{oy} and k_y are the material constants, and can be determined from, for example, the straight lines in Fig. 4. which were obtained from

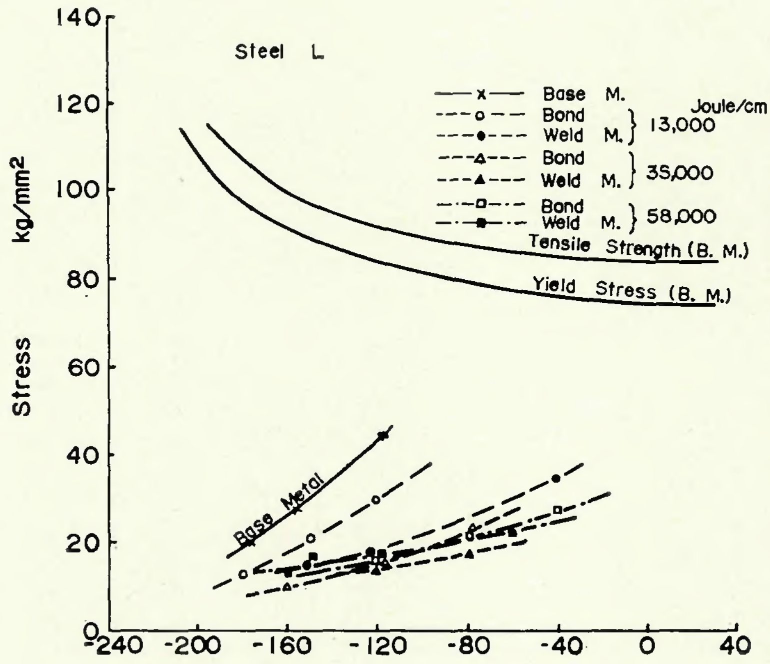


Fig. 4—Correlation between fracture stress (modified gross stress) and temperature, where notch length c is 120 mm (steel L)

Table 1—Chemical Compositions and Mechanical Properties

Steel[a]	Kind of steel	Plate thickness, mm	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	Al	Nb	Y.S. kg/mm²	T.S. kg/mm²	Elongation, %
			Chemical compositions, %[b]													Mechanical properties[c]		
A	HW50(HT60)	25	0.13	0.43	1.22	0.019	0.014	....	....	0.21	....	0.06	....	—	....	52.0	64.0	42.0
B	HW50(HT60)	25	0.15	0.26	1.22	0.012	0.013	....	....	....	....	0.064	....	....	....	53.0	64.0	23.2
C	HW45(HT60)	28	0.14	0.36	1.21	0.011	0.010	0.07	0.50	0.04	0.097	0.034	....	0.029	....	58.8	68.9	27.0
D	HW50(HT60)	28	0.16	0.39	0.77	0.010	0.012	0.34	....	....	....	0.030	....	0.034	....	60.6	68.5	28.5
E	HW50(HT60)	30	0.12	0.36	1.21	0.017	0.011	0.21	0.21	0.12	0.03	....	....	0.039	....	53.0	63.7	47.6
F	HW50(HT60)	25	0.13	0.33	1.51	0.024	0.014	0.04	0.21	0.03	0.13	....	....	....	....	55.0	68.5	21.9
G	HW45(HT60)	25	0.15	0.47	1.37	0.015	0.008	0.07	0.02	....	0.05	0.046	....	0.01	0.038	47.7	64.6	24.5
H	HW63(HT70)	40	0.13	0.41	1.02	0.013	0.012	0.21	1.19	0.39	0.30	<0.01	....	0.010	....	65.7	76.8	25.0
I	HW70(HT80)	25	0.14	0.31	1.47	0.010	0.005	0.10	....	....	0.61	....	0.003	0.056	0.040	78.2	82.3	18.3
J	HW70(HT80)	28	0.12	0.27	0.86	0.006	0.004	0.26	0.80	0.47	0.45	0.043	0.0025	0.032	....	85.0	89.0	25.0
K	HW70(HT80)	20	0.12	0.22	0.95	0.026	0.017	0.29	0.90	0.65	0.54	0.06	0.003	....	....	82.4	87.8	28.0
L	HW70(HT80)	20	0.11	0.30	0.99	0.015	0.11	0.24	1.04	0.44	0.36	....	....	....	....	82.4	86.2	34.3
M	HW90(HT100)	20	0.15	0.24	0.78	0.013	0.009	0.17	1.26	0.70	0.55	0.07	....	....	....	101.9	105.7	22.0
N	QT.A1-kill,33	19	0.09	0.29	1.17	0.011	0.005	....	....	....	....	....	....	....	....	36.0	49.0	48.0
P	9% Ni[d]	13	0.07	0.26	0.48	0.016	0.010	9.38	....	....	....	....	....	....	....	69.0	74.4	26.8

[a] Steels except G are quenched and tempered.
[b] Check analysis.
[c] Y.S.—yield strength; T.S.—tensile strength.
[d] Ladle analysis instead of check analysis.

round bar tensile test at several temperatures.

The design stress for the prevention of welded structures from brittle fracture is given by the following equation:

$$\sigma = \sigma_y/n \tag{4}$$

where σ_y is the yield stress at service temperature, and n is the safety factor.

Let some parts of welded structures be approximately the infinite plate with a crack of $2c$ long under tensile stress σ in the direction perpendicular to the crack at infinity. The Griffith-Orowan energy equation as a criterion for the initiation of unstable fracture is expressed as follows:

$$\frac{\pi\sigma^2 c}{E} = 2S_i \tag{5}$$

From eqs (2) ~ (5), the following equation is obtained:

$$e^{\frac{2(k_i + k_y)}{T_k}} = \frac{2E}{\pi}\cdot\frac{S_{oi}}{\sigma_{oy}^2}\cdot\frac{n^2}{c} \tag{6}$$

In other words, the brittle fracture initiation temperature in absolute temperature T_k, can be obtained from eq (6) for an arbitrary crack length $2c$ with the safety factor n by using various material constants, k_i, k_y, S_{oy} and σ_{oy}, as shown, for example, in Fig. 7.

Results of Round Bar Tensile Test

Correlations between the yield stress, the tensile strength and the temperature for the base metal, the bond and the weld metal are obtained by using the round bar tensile test specimen of 6 mm diameter.

The round bar specimens for bond is produced by the following procedures: At first, the measured temperature-time diagram at the bond in deep notch test specimen with welded joint, which are welded under the given welding conditions, is drawn. Then, the identical thermal cycles to the measured one are provided to the round bar by means of the synthetic thermal cycle apparatus. Finally, the tensile test specimen is machined from the bar with thermal cycles.

In case of the multilayers, only the first two cycles, which are considered metallurgically to be the most effective on the steel quality, are provided.

In case of steel L in Tables 1 and 2 as an example, correlations are shown in Fig. 3 between the logarithms of yield stress σ_y as well as tensile strength σ_u and the reciprocal of absolute temperature for the base metal for the bond and the weld metal, with heat inputs of 13,000

Table 2—Charpy V-Notch Transition Temperatures

Steel	15 ft-lb v^Tr15 °C	Energy v^TrE °C	Shear, % v^Trs °C
A	− 75	− 33	− 23
B	− 94	− 42	− 47
C	−116	− 72	− 59
D	− 81	− 52	− 62
E	−105	− 66	− 50
F	− 87	− 62	− 50
G	− 38	− 19	− 24
H	<−100	− 86	− 85
I	−110	− 90	− 85
J	− 89	− 58	− 50
K	− 93	− 73	− 58
L	<−100	− 87	− 92
M	− 70	− 25	− 27
N	−125	−105	−110
P	<−196	−174	<−196

joules/cm (manual shielded-arc welding) in as-welded condition and stress relieving heat treatment of 600° C × 1 hr, 35,000 and 58,000 joules/cm (automatic submerged-arc welding) as-welded.

From the linear relationship, the material constants σ_{oy} and k_y in eq (3) can be obtained, and are presented in Table 3.

Deep Notch Test

Correlation between the modified gross stress at fracture in deep notch test specimen for $c = 80$ mm, $f(\gamma)\cdot\sigma$, in eq (1) and the temperature for the base metal are shown in Fig. 4 for the bond and the weld metal with various heat inputs, and the yield stress-, the tensile strength-temperature curves for steel L.

In comparing the fracture stress for various steel qualities at identical temperature, the base metal is the highest, while the bond and the weld metal deposited manually and automatically are lower in order.

The plastic surface energies at fracture S_i can be computed from the notch length and the fracture stress by applying eq (1) at various temperatures.

Correlation between the logarithm of S and the reciprocal of absolute temperature is shown in Fig. 5. It is noted that the temperature dependencies of plastic surface energy for all steel qualities, except that for the weld metal deposited automatically with large heat input, are nearly identical. From these straight lines the material constants S_{oi} and k_i in eq (2) are obtained and presented in Table 3. In addition, the inclination of line is not affected by the stress-relieving heat treatment.

When the material constants σ_{oy}, k_y, S_{oi} and k_i are determined, the correlation between the half crack

Table 3—Material Constants (Steel L)

Kind of materials	Material constants[b] S_{oi}, kgmm/mm²	$2k_i$, °K	σ_{oy}, kg/mm²	k_y, °K	Brittle fracture initiation temperature $[T_i]_{c=40}$, °C
Base metal	143	338	65	37	−175
Base metal (stress relieved)	92	357	65	47	−161
Bond (13,000)[a]	96	405	59	48	−150
Weld metal (13,000)	53	378	65	37	−136
Bond (35,000)	47	458	70	34	−100
Weld metal (35,000)	12	282	51	43	−113
Bond (58,000)	47	458	76	30	− 93
Weld metal (58,000)	10	211	51	43	−133

[a] Data in parentheses are heat input in joules/cm.
[b] $S_i = S_{oi}e^{-2k_i/T_K}$; $\sigma_y = \sigma_{oy}e^{k_y/T_K}$.

length and the brittle fracture initiation temperature at the stress level of σ_y/n, where σ_y is the yield stress at the temperature concerned, in an infinite plate subjected to the uniform tensile stress in the direction normal to the crack can be obtained by applying eq (6). When the applied stress level is $\sigma_y/2.5$, the correlations for various steel qualities computed from the material constants in Table 3 are shown in Fig. 6.

It is noted that the brittle fracture initiation temperature T_i increases with crack length. If the maximum crack length which might be overlooked at inspection after welding is assumed to be 80 mm, the half crack length of 40 mm is considered to be a fundamental crack length for evaluation of brittle fracture initiation temperature of steel quality. Consequently, the brittle fracture initiation temperature for $c = 40$ mm, $[T_i]_{c=40}$ is very significant. $[T_i]_{c=40}$ for various steel qualities are presented in Table 3.

In comparing $[T_i]_{c=40}$ for the bond with heat inputs of 13,000, 35,000 and 58,000 joules/cm with that for the base metal, the increases in brittle fracture initiation temperature are 26, 76 and 83° C respectively. Therefore, the embrittlement of bond by the automatic welding is serious. In case of the weld metal, the increases in brittle fracture initiation temperature are 40, 68 and 46° C respectively.

For the manual welding, the bond is better than the weld metal. On the contrary, the bond is worse than the weld metal for the automatic welding.

By the heat treatment of stress relieving, the brittle fracture initiation

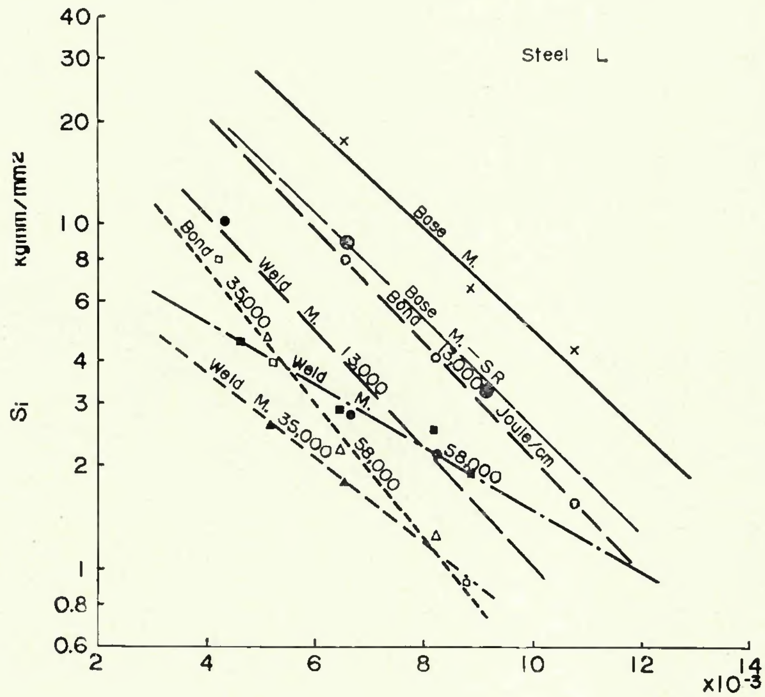


Fig. 5—Correlation between plastic surface energy and reciprocal of absolute temperature (steel L)

temperature for the base metal shifts to the higher temperature side by 10 ~ 20° C, and those for the bond and the weld metal deposited manually do not vary.

An example of the HT60 (60 kg/mm²
high strength steel), the results for steel B welded with the heat inputs of 15,000 (manual), 39,000 and 60,000 (automatic) joules/cm are shown in Fig. 7. From Fig. 7 it can be seen that the embrittlement of bond is unchanged irrespective of manual and the automatic welding.

The influence of heat input on the brittle fracture initiation temperature of weld metal for various high strength steels was investigated by Subcommittee EW, Irons & Steel Committee, Japan Welding Engineering Society. The steels tested were delivered by all major steel companies in Japan, and are

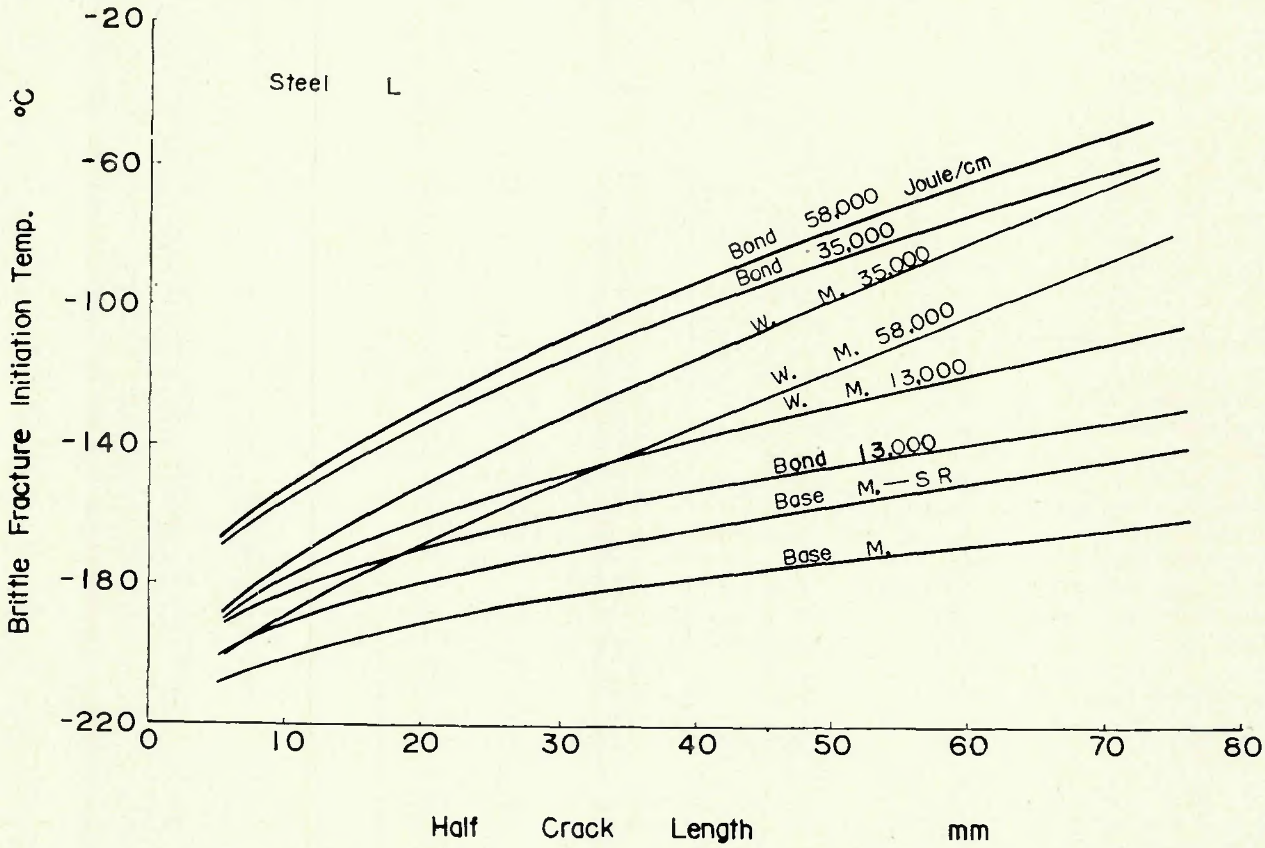


Fig. 6—Correlation between brittle fracture initiation temperature and half crack length for HT 80 (steel L, $\sigma = \sigma_y/2.5$)

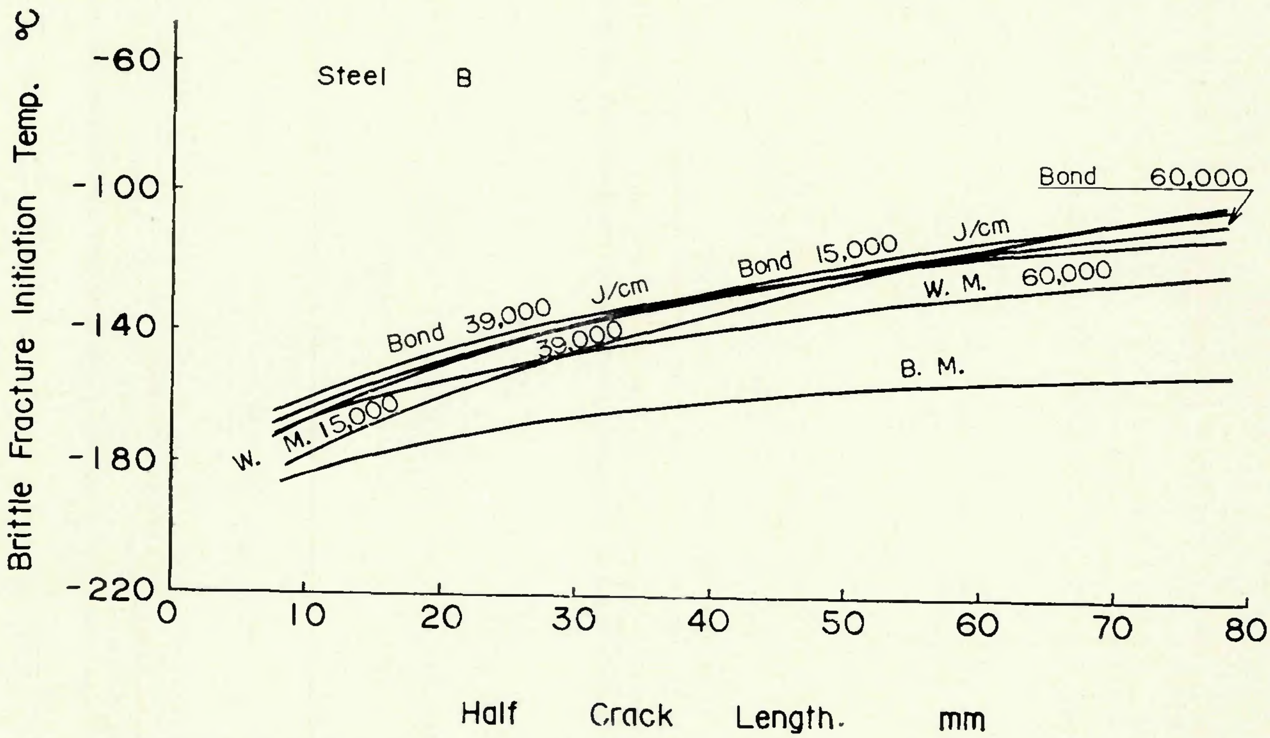


Fig. 7—Correlation between brittle fracture initiation temperature and half crack length for HT 60 (steel B, $\sigma = \sigma_y/2.5$)

Fig. 8—Correlation of increase in brittle fracture initiation temperature of bond from base metal, $[\Delta T_i]_{c=40}$, and heat input [$\sigma = \sigma_y$ (base metal)/2.5]

steels A to M in Table 1.

The differences of brittle fracture initiation temperature between bond and base metal for c = 40 mm for various heat inputs are shown in Fig. 8. The applied stress is $\sigma_y/2.5$, where σ_y is the yield stress for base metal instead of bond at the temperature concerned.

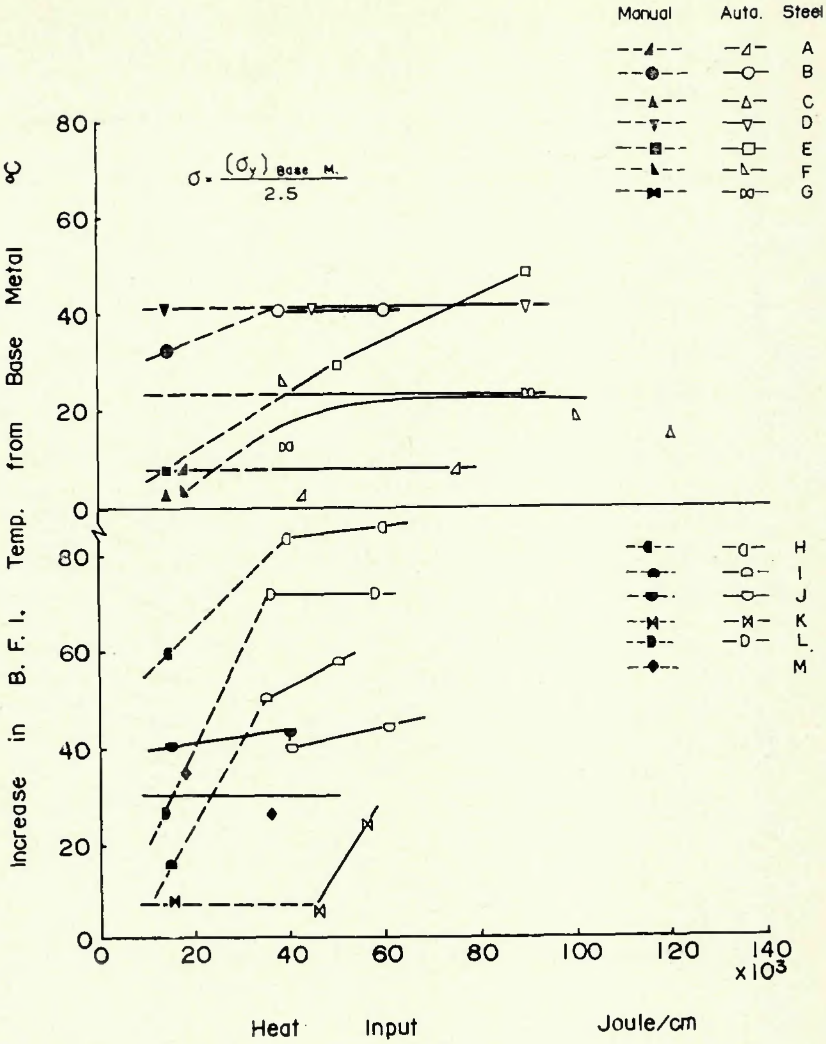
Of course, in cases where n is 1.5, 2.0, 2.5, 3.0 and σ_y is, respectively, the yield stresses for bond or base metal at the temperature concerned and for base metal at room temperature, the brittle fracture initiation temperature-half crack length curves are shown in Fig. 6, and curves as shown in Fig. 8 can be easily obtained mathematically.

It is to be noted in Fig. 8 that the heat input does not give any appreciable influence on the welding of HT60 and, therefore, the heat input control is generally not necessary. Meanwhile, bond embrittlement becomes more serious when the heat input increases in automatic welding of HT70 and HT80, although some HT80 is slightly affected by the heat input. In the case of HT100, the heat input in manual welding does not affect bond embrittlement.

The effect of heat input on the brittle fracture initiation temperature of weld metal for various high strength steels in the manual and automatic weldings is shown in Fig. 9 for the steels tested. The dotted lines link two points corresponding to two different heat inputs with the identical welding material. It is to be noted in Fig. 9 that the brittle fracture initiation temperature for the weld metal is rather low and that the effect of heat input is considered to be negligible.

Several liquid oxygen and nitrogen storage tanks have been recently built, and LMG storage tanks are being constructed with 9% Ni steel in Japan. The test results for quenched-and-tempered 9% Ni steel, steel P, are shown in Fig. 10. The welded joint were deposited manually with the electrode "Incoweld A (70% Ni)." The brittle fracture initiation characteristics of base metal and bond are excellent, and it is proved that 9% Ni steel is suitable for the liquid nitrogen storage tank exposed to low temperature of −196° C, and the tank has been safely operated.

Since the weld metal of 70% Ni is extremely ductile, the weld metal



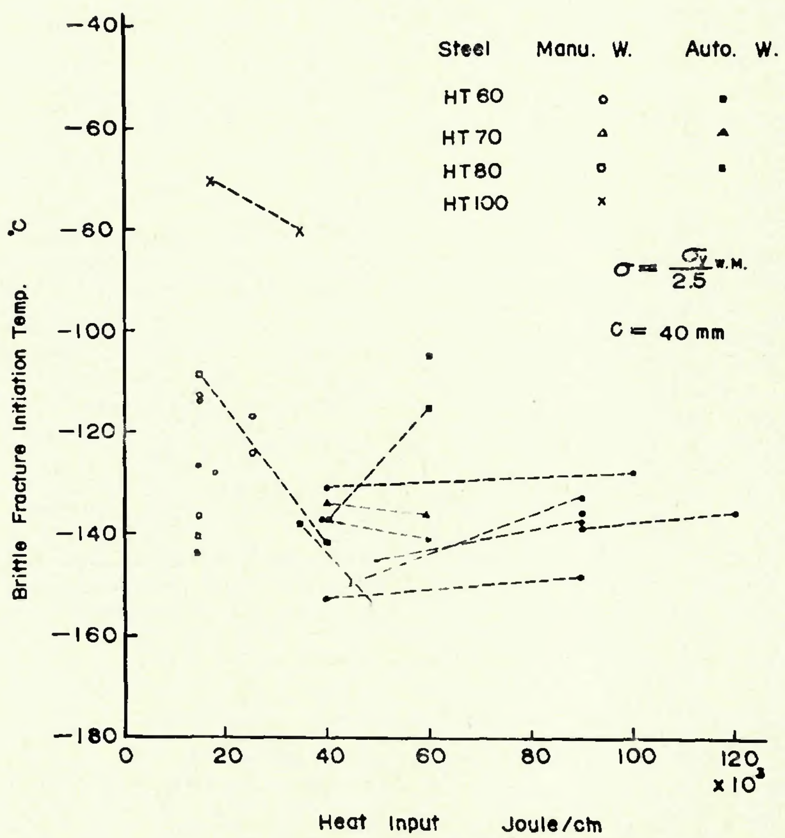


Fig. 9—Correlation between brittle fracture initiation temperature of weld metal and heat input [$\sigma - \sigma_y$ (weld metal) /2.5, c = 40 mm]

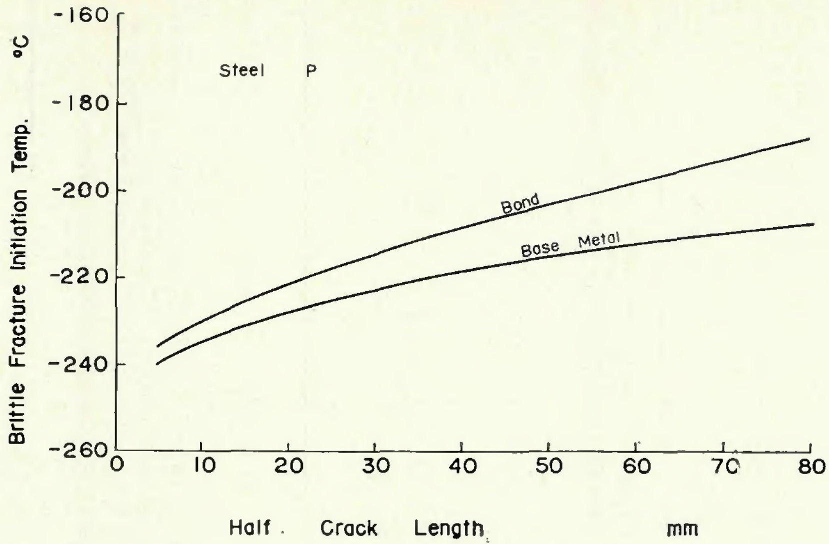


Fig. 10—Correlation between brittle fracture initiation temperature and half crack length for 9% Ni steel (steel P, $\sigma = \sigma_y/2.5$)

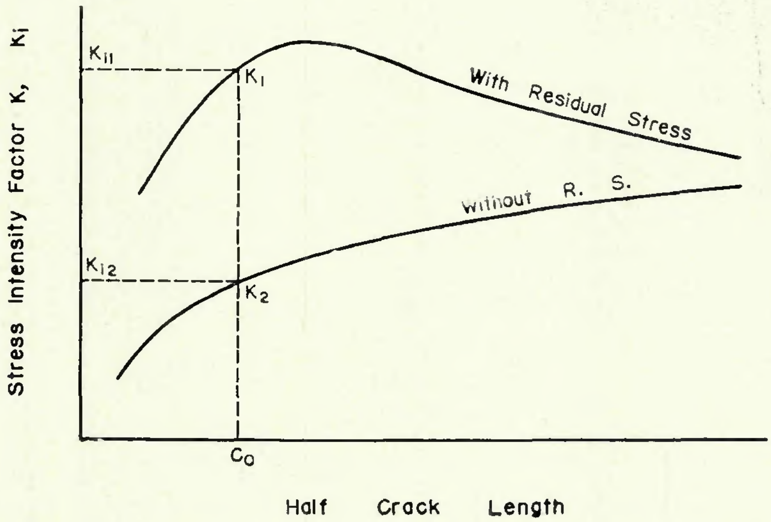


Fig. 12—Correlation between stress intensity factor, K, and K_i and half crack length

fractures not in a brittle manner but in a ductile manner even at about −196° C. The net stress at fracture for weld metal lies on the tensile strength-temperature curve which was obtained from the round bar tensile test specimen made of all-deposited metals.

Recently, the effect of nickel content of electrode on the fracture initiation characteristics of welded joints for quenched-and-tempered 9% Ni steel plate was investigated as one of the 1967 programs of Subcommittee EW, Iron & Steel Committee of Japan Welding Engineering Society. Even when the testing temperature is as low as −196° C, the weld metal of welded deep notch test specimens with the notch length of 80 mm, as shown in Fig. 2, fracture not in a brittle manner, but in a ductile manner for 70, 50, 40, 35, 30, 12% Ni-content electrodes.

Effect of Welding Residual Stress on Brittle Fracture Initiation Temperature

In many cases of brittle fracture of welded structures, the brittle fracture initiated at the welded joint including the cross or the T points with a notch, where the welding residual stress superimposed on the embrittled bond or weld metal where a notch exists.

Since the brittle fracture initiation

Table 4—Maximum Tensile Residual Stress for Various High Strength Steels

	σ_y[a]	σ_1[b]	σ_1/σ_y	σ_2[c]	σ_2/σ_y
HT 60	50	42	.84	53.7	1.08
HT 70	60	44	.73		
HT 80	70	45	.64	47.5	0.69
HT 100	90	48	.53		

[a] Guaranteed yield point.
[a, b, c] In kg/mm².

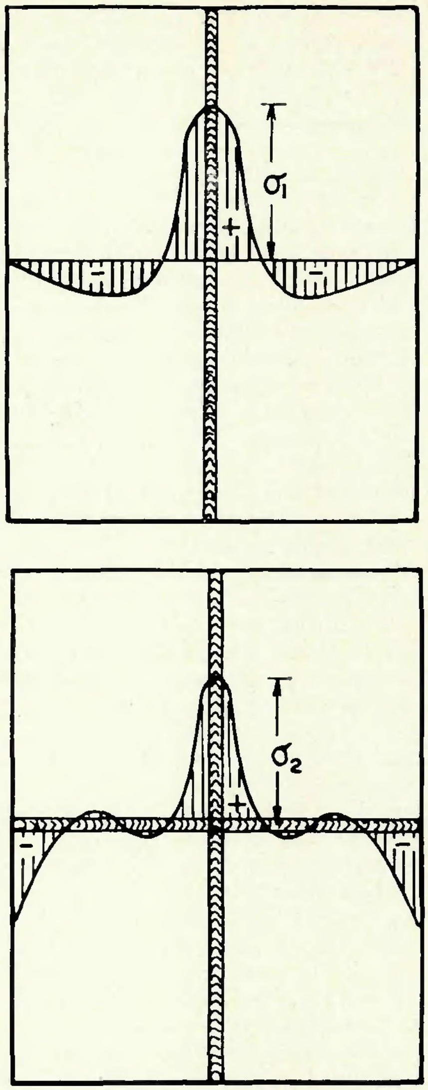


Fig. 11—Welding residual stress distribution. Top (a)—longitudinal joint; bottom (b)—cross joint

characteristics of bond and weld metal can be evaluated by using the deep notch test specimen with welded joint as mentioned previously, the effect of residual stress is discussed below.

Residual Stress Distribution

The distributions of welding residual stress in the direction of longitudinal weld along the midlength or the transverse weld for the longitudinally and the crossly welded joints, respectively, are shown schematically in Fig. 11. By denoting the maximum residual tensile stresses for longitudinal and cross joints as σ_1 and σ_2, respectively, σ_1 and σ_2 for mild steel and various high strength steels are presented in Table 4. The ratios of σ_1/σ_y and σ_2/σ_y, where σ_y is the yield point, decrease as increasing strength.

Effect of Residual Stress on Brittle Fracture Initiation Temperature

Let us consider the brittle fracture initiation when a crack is located across the longitudinal joint, along the bond or in the weld metal of transverse bead for cross joint. In other words, the tip of crack is located in the base metal, the bond and the weld metal, respectively, under the superimposition of residual stress.

The brittle fracture initiates when the Griffith-Orowan energy equation expressed as eq (1) is satisfied. According to the Irwin's expression, an unstable fracture initiates when the stress intensity factor K, which is the strain energy release rate, is equal to K_c which is similar to the plastic surface energy. Since the problem of fracture initiation is concerned, K_i is used instead of K_c in this paper.

An infinite plate, in which a crack of $2c$ long exits, may be subjected to a uniform tensile stress at infinity in the direction perpendicular to the crack. In such a case $K = \sigma\sqrt{c}$ when the welding residual stress as shown in Fig. 11. is superposed on the crack and K is obtained by the following equation:[2]

$$K = \int_{-c}^{c} P(x) \left[\frac{2 \sin \frac{\pi(c+x)}{l}}{\pi l \sin \frac{2\pi c}{l} \sin \frac{\pi(c-x)}{l}} \right]^{1/2} dx \quad (7)$$

where P = residual stress distribution, $2c$ = crack length, l = plate width, and x = distance from center line of plate in the direction of crack extension.

Correlations between the stress intensity factor K and half crack length c, with and without residual stresses, are shown in Fig. 12. When the brittle fracture initiates from a crack of $2c_o$ long at a stress level of σ, K for c_o on the abscissa, or K_1 and K_2, with and without residual stresses, are equal to K_i or K_{i1}, and K_{i2}, respectively.

Correlations between S_i and the temperature for the base metal, the bond and the weld metal which were obtained by using the deep notch test with and without welded joint, respectively, are shown as for example in Fig. 5. Therefore, correlations between the logarithm of $K_i \left(= \sqrt{\frac{2E}{\pi} S_i} \right)$ and the reciprocal of absolute temperature for various qualities are similar to those shown in Fig. 5, and the corresponding K_i vs. temperature curve is shown schematically in Fig. 13. By taking K_{i1} and K_{i2} obtained in Fig. 12 on the K_i-T curve in Fig. 13, the brittle fracture initiation temperature in the cases with and without residual stresses, T_1 and T_2, respectively, can be determined. Then the difference between T_1 and T_2, $\triangle T_{ir}$, is an increase in brittle fracture initiation temperature caused by the super-imposition of residual stress.

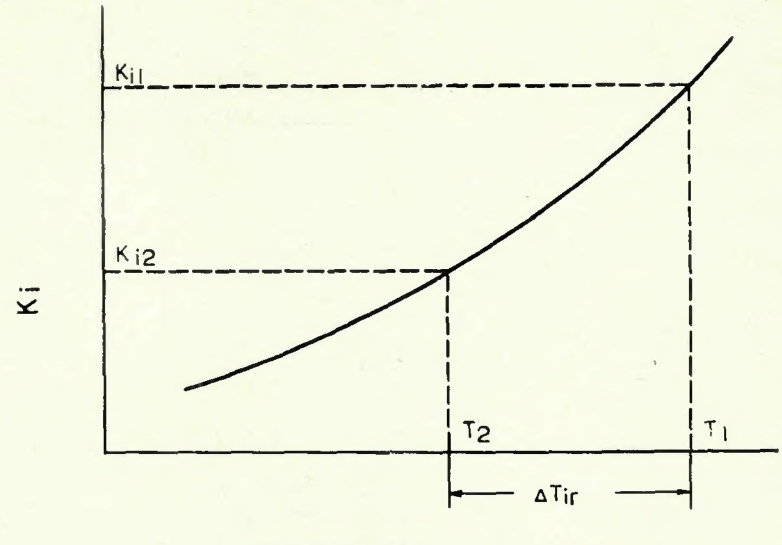


Fig. 13—Definition of increase in brittle fracture initiation temperature caused by residual stress, ΔT_{ir}, for $c = c_o$

The correlation between $\triangle T_{ir}$ and the yield point for high strength steels presented in Table 1 for c = 20 and 40 mm at the stress level of (σ_y) Base M.—Room Temp/2 in the cases of longitudinal and cross joints, respectively, are shown in Fig. 14. In general, the distribution of welding residual stress around the cross joint in the welded structures might be probably similar to the case of longitudinal joint as shown in Fig. 11(a). Therefore, it can be estimated from the viewpoint of safety design that $\triangle T_{ir}$ in the case of

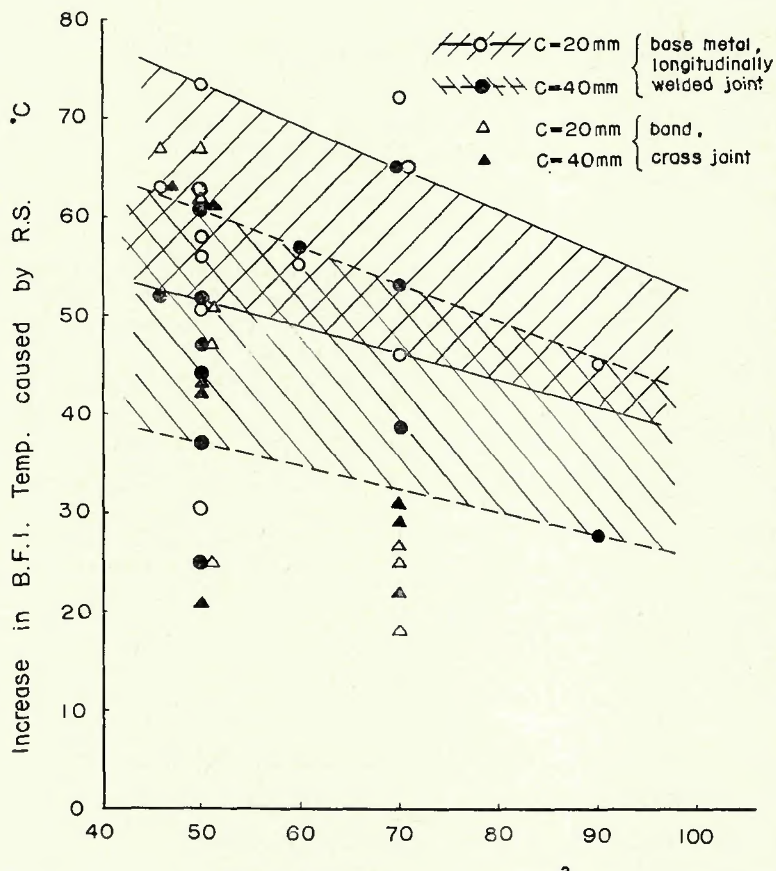


Fig. 14—Correlation between increase in brittle fracture initiation temperature caused by residual stress, ΔT_{ir}, $(\sigma = [\sigma_y/2]_{B.M.-R.T.})$ and yield stress of steel

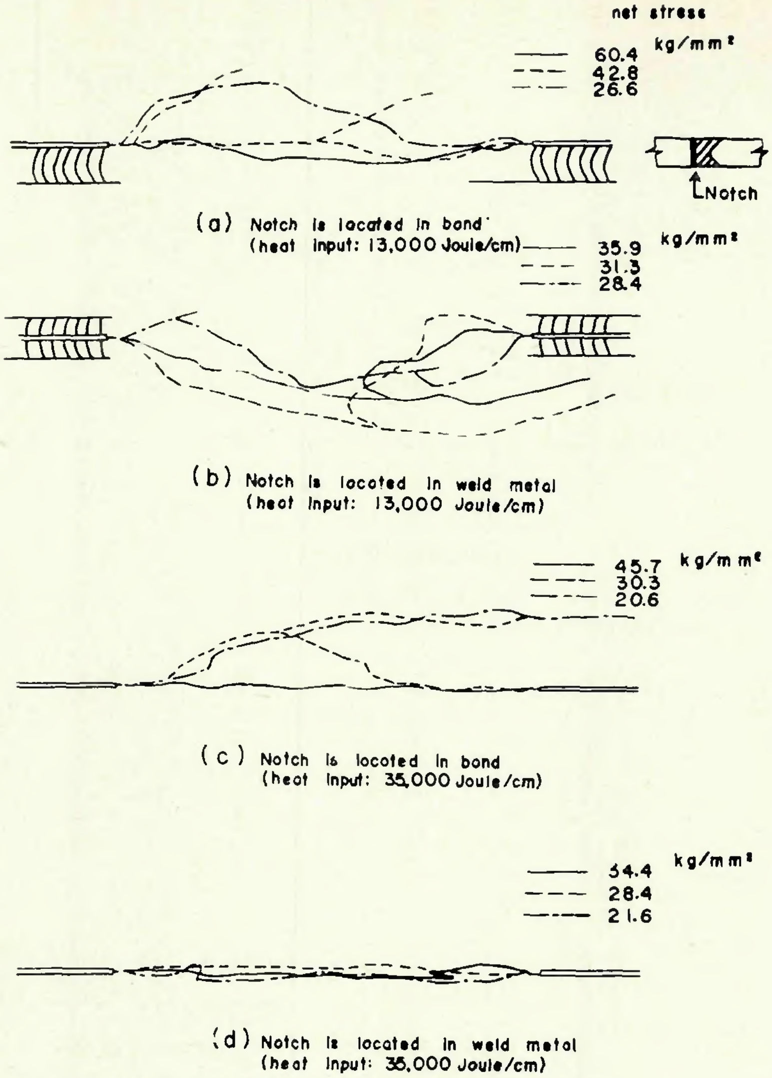


Fig. 15—Crack path in welded specimen for HT 80 (steel L)

T or cross joints in the welded structures ranges from 40 to 70° C as shown with upper two zones in Fig. 14.

Consequently, the brittle fracture initiation temperature-half crack length curves as shown in Figs. 6, 7 and 10 should be raised to the higher temperature side by ΔT_{ir} for T and cross joints in as-welded condition.

Crack Path

When a brittle crack initiates in the welded joint which is laid in the direction normal to the applied stress, the crack propagates along the path affected by the welding residual stress and steel quality.

In the case of mild steel, the brittle crack curves to the base metal. This is because residual tensile stress as high as the yield stress in the direction of welded joint exists in the vicinity of welded joint.

In case of the 80 kg/mm² high strength steel shown in Fig. 15, the brittle crack propagates straight along the bond or in weld metal deposited manually with a heat input of 13,000 joules/cm, when the net stress at fracture exceeds 40 kg/mm². On the other hand, the brittle crack curves to the base metal when the net stress is less than 40 kg/mm². The crack propagates straight for automatic welds with heat inputs of 35,000 and 58,000 joules/cm. For automatically welded 60 and 70 kg/mm² high strength steels, the brittle crack propagates straight for the automatic welding.

In any case, when the welding re-residual stress is relieved by the heat treatment, the brittle crack propagates straight in the direction normal to the external load along the bond or in the weld metal.

Conclusion

The authors succeeded in the evaluation of brittle fracture initiation characteristics of welded joints without residual stress by using the deep notch test specimen with welded joint. The effects of welding heat input on the brittle fracture initiation temperature for various high strength steels and 9% Ni steel manufactured presently in Japan were investigated.

Next, the effects of welding residual stress on the brittle fracture initiation temperature for various high strength steels have been investigated.

Lastly, the characteristics of brittle crack path in the welded joint region for high strength steel was clarified.

Acknowledgement

The authors wish to thank Professor Kanazawa and members of Subcommittee I, Welding Committee, Society of Naval Architects of Japan, and members of Subcommittee, Iron & Steel Committee, Japan Welding Engineering Society, for their helpful discussions.

The authors thank S. Kitamura, M. Tani, M. Sakuma and H. Murakami for their assistance in performance of the experiment.

Further, the authors wish to express their thanks to Professor W. J. Hall, University of Illinois, for his useful comments, and all steel and electrode companies for their contributions of delivering materials and performance of the experiment concerned.

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