Prevention of Solidification Crack in Welding under Pulsating Loads†

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Abstract

The structures in service condition such as bridges, offshore structures and so on are always suffered the pulsating loads by moving vehicles, the waves, current or wind, etc. So, repair, reinforcement or reconstruction works by welding on these structures are done under the pulsating loads.

In this paper, the weld cracking test under the pulsating loads is carried out and the deciding method of the solidification crack is proposed with consideration based on welding mechanics.

(1) Under the pulsating loads, there is a possibility which the solidification crack initiates in the zone, where no solidification crack initiates from Trans-Varestraint cracking test. Therefore, deciding the solidification crack initiation under the pulsating loads from the resluts of Trans-Varestraint cracking test, the accuracy of evaluation is low.

(2) The accumulation strain, ε_t, by which the weld metal was repeatedly applied at a short time from the liquidus to the solidus was proposed as a measure for deciding the solidification crack initiation under the pulsating loads. The solidification crack initiates when ε_t is larger than critical strain, ε_{cr}, which is the materials characterisation.

(3) ε_t was expressed with the relative root gap opening displacement, $\Delta\delta$, which can be easily measured before welding. Moreover, the practical deciding equation for solidification crack initiation under the pulsating loads using $\Delta\delta$ was derived.

(4) For the case that the uniform pulsating loads are applied, the validity of the practical deciding equation was concretely shown.

KEY WORDS : (Weld cracking test)(Trans-Varestraint cracking test)(Pulsating loads)(Solidification crack)(Hot crack)(Prevention of solidification crack)

1. Introduction

The structures in service condition such as bridges, offshore structures and so on are always suffered the pulsating loads by moving vehicles, the waves, current or wind, etc. So, repair, reinforcement or reconstruction works by welding on these structures are done under the pulsating loads.

The authors have already carried out the weld cracking test under the pulsating loads for the bridge, and have shown that there was a possibility of hot crack initiation in the weld metal[1)]. Moreover, it was also shown that the cracks can be classified into that of solid-liquid state and that of solid one by conducting the high temperature tensile test[2)] on the weld metal. The former is called a solidification crack and the latter is a HS (Hot Crack in Solid State)-type one.

The susceptibility of the solidification crack has been evaluated from the relation of the temperature range where the crack initiates and applied strain obtained by Trans-Varestraint cracking test, in which external load is applied once[3)]. On the other hand, in welding under the pulsating loads, the loads are applied on the weld metal not for once but repeatedly. Therefore, it is considered that the susceptibility of the solidification crack on the weld metal under the pulsating loads which is evaluated from the results obtained by Trans-Varestraint cracking test, etc. is not always reliable enough.

In this paper, the weld cracking test under the pulsating loads is carried out and a measure for the solidification crack initiation under the pulsating loads and the deciding equation for the crack initiation are proposed with consideration based on welding mechanics. And the validity of them is concretely shown.

2. Weld Cracking Test under the Pulsating Load and Trans-Varestraint Cracking Test

Material of the specimen is JIS-SM58, and thickness of it is 16mm. Ultra low hydrogen welding electrode JIS-D4316(4mm$^{\phi}$) are used for welding. **Table 1** shows chemical composition and mechanical properties of specimen. The single pass welding is performed with 22kJ/cm heatinput.

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Table 1 Chemical composition and mechanical properties

Item	Grade	Size (mm)	Chemical composition (%)					σY (MPa)	σU (MPa)	El. (%)
			C	Si	Mn	P	S			
Steel	SM58	16	0.10	0.26	1.71	0.018	0.003	690	740	34
Electrode	D4316	Φ4	0.04	0.32	0.04	0.003	0.001	410	450	33

2.1 Weld cracking test

Figure 1 shows the H-type and I-type slit specimen, respectively.

The pulsating loads were applied by fatigue test machine[1] and stress ratio ($\sigma_{min}/\sigma_{max}$) was 0. Before welding was performed, clip gages were attached at the root groove on the middle of weld line and the relative root groove displacement, $\Delta\delta$, caused by the external pulsating loads was measured.

Figure 2 shows the result of the weld cracking test under the pulsating loads by symbol. According to this, if the frequency of applied strain, f, becomes larger, critical relative displacement for a weld crack initiation, $\Delta\delta_{cr}$, has the tendency to be small in spite of the difference of the model. Comparing with H-type and I-type slit specimen, $\Delta\delta_{cr}$ of H-type slit specimen is larger than that of I-type slit specimen regardless of f. Therefore, it is known that the susceptibility of the crack on I-type slit specimen is higher than that on H-type slit specimen. This is considered to depend upon the differences between in-plane stiffness of both specimens. This will be discribed in detail in section 4. In the weld crack, paying attention to the solidification crack and the HS-type one, in the case that f is small, $\Delta\delta_{cr}$ of the solidification crack is larger than that of the HS-type one. On the contrary, if f becomes larger, $\Delta\delta_{cr}$ of the solidification crack seems to be smaller than that of the HS-type one. The solidification crack is only discussed in this paper and the HS-type crack will be done in the next report.

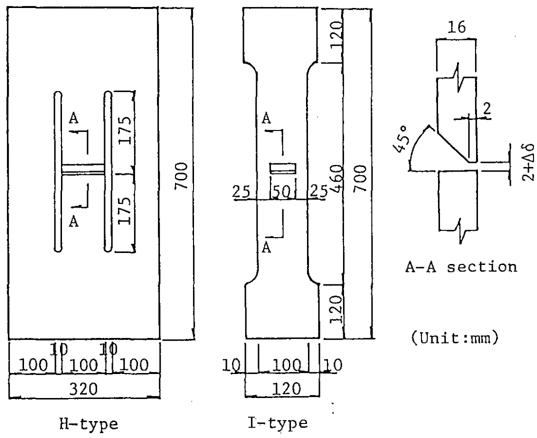


Fig.1 Specimen for weld cracking test

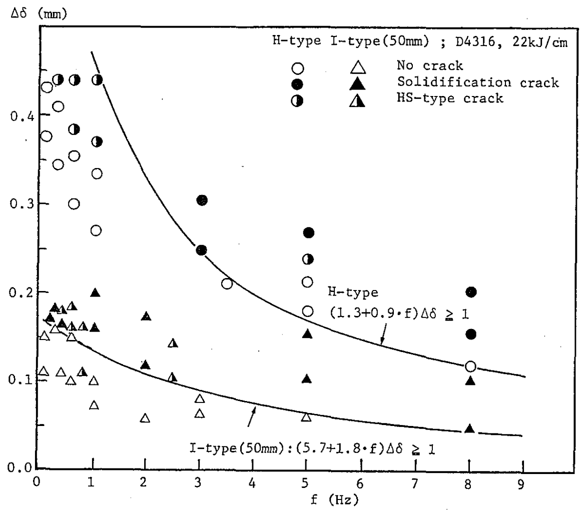


Fig.2 Experimental results of weld crack test under pulsating loads.

2.2 Trans-Varestraint cracking test

According to the results of Trans-Varestraint cracking test on D4316 (**Fig.3**)[2], critical strain of the solidification crack, ε_{cr} is 1% and CST (Critical Strain Rate to Temperature Drop) is 2.1×10^{-4} /℃ . Therefore, the solidification crack initiates only in the range where applied strain, ε , is larger than 1% and CST is faster than 2.1×10^{-4} /℃ . BTR (Brittle Temperature Range) in Trans-Varestraint cracking test is within the temperature from 1500℃ to 1350℃ . Based on this, the solidification crack initiation under the pulsating loads is guessed.

According to the result of the temperature observation in weld cracking test under the pulsating loads, the average cooling rate of temperature from 1500℃ to 1350℃ is 133 ℃ /s. Multiplying the average cooling rate by CST obtained from Trans-Varestraint test, the critical strain rate under the pulsating loads, $\dot{\varepsilon}_{cr}$, is 2.79×10^{-2}/s. Rearranging the relation between applied strain, ε , and strain rate $\dot{\varepsilon}$, **Figure 4** shows the result of weld cracking test under the pulsating loads.

Besides, ε and $\dot{\varepsilon}$ were obtained from Fig.2 as follows. First, as described in previous report[2], in the case that f = 5.5Hz and $\Delta\delta$ = 0.065mm, ε is 1.1%. Based on this, assuming that $\Delta\delta$ and ε are in proportion, the following equation is obtained.

$$\varepsilon = 1.1 \cdot \Delta\delta \text{(Fig.2)} / 0.065\ (\%)$$

$$\dot{\varepsilon} = 2 \cdot f \cdot \varepsilon\ (1/s)$$

In the Fig.4, the solidification crack initiates even in the range (e.g. points A and B) where the crack is anticipated not to initiate from the result of Trans-Varestraint cracking test. This means that estimating the solidification crack initiation, which external loads are applied repeatedly in the weld metal from the reslut of

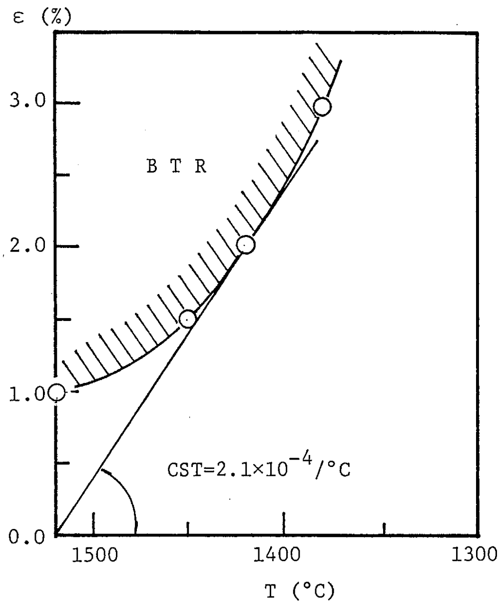


Fig.3 Experimental results of Trans-Varestraint cracking test of D4316.

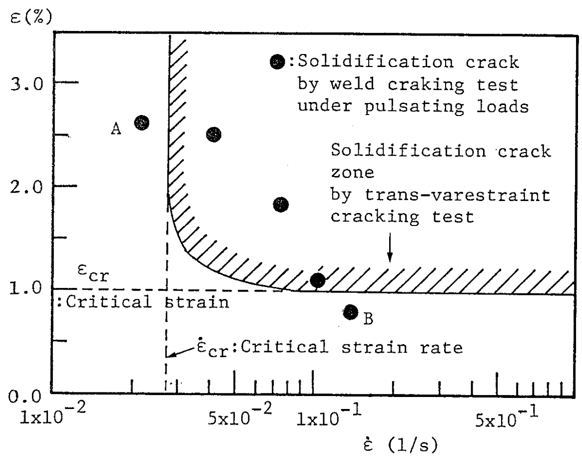


Fig.4 Relation between strain rate, $\dot{\varepsilon}$, and applied strain , ε , by pulsating loads.

Trans-Varestraint cracking test, the accuracy of evaluation is low.

3. Consideration of the Solidification Crack under Pulsating Load

3.1 Initiation of the solidification crack

Generally, whether the solidification crack initiates or not is related with the crystallization in solidificating process of the weld metal and the behavior of residual liquid[4]. Therefore, it is anticipated that the solidification crack initiates when crystallization of the weld metal is prevented or when residual liquid which plugs up the crack cannot follow.

Here, considering the case under pulsating loads, strain ε due to external loads is repeatedly applied on the solidificating weld metal. This is considered to be a main cause that the crystallization and the following of residual liquid are prevented. So, the solidification crack initiates when the repeatedly applied strain, ε , in the weld metal becomes larger than the critical strain, ε_{cr}, for the solidification crack. By the way, it is difficult to decide ε , which is directly due to the initiation of crack, among repeatedly applied strain ε at a short time, Δt, from the liquidus to the solidus. In this paper, the accumulated value, ε_t, of applied strain in Δt is regarded as one of the measure to evaluate the solidification crack initiation under the pulsating loads. Therefore, whether the solidification crack initiates or not is described as following equation.

$$\varepsilon_t \geqq \varepsilon_{cr} \tag{1}$$

where, ε_t : accumulated strain which the weld metal is repeatedly applied at a short time from the liquidus to the solidus

ε_{cr}: critical strain for the solidification crack which is materials characterisation

3.2 Applicability of relative root gap opening displacement as a measure of crack initiation

The relation between the relative root gap opening displacement, $\Delta\delta$, and accumulated strain, ε_t, is considered, here. Then, as a substitute for ε_t, the applicability of $\Delta\delta$ as a measure by which the solidification crack initiation under the pulsating loads is evaluated is investigated.

3.2.1 In case without external loads

As ε_w is produced by the restraint of the base metal for free shrinkage of the weld metal, ε_t is decided by welding condition, stiffness of the welded joint and so on in case that no external loads affect on the weld metal. So, the Eq.(1) of the solidification crack initiation becomes as follows.

$$\varepsilon_t = \varepsilon_w \geqq \varepsilon_{cr} \tag{2}$$

where, ε_w: free contraction strain of the weld metal

3.2.2 In case with external loads once applied

In this case, strain ε_L due to the external loads excepting ε_w is added. Therefore, the Eq.(1) becomes as follows.

$$\varepsilon_t = \varepsilon_w + \varepsilon_L \geqq \varepsilon_{cr} \tag{3}$$

where, ε_L: strain due to external loads

By the way, considering that affecting strain to the weld metal by the external loads, ε_L, is proportional to the displacement of root gap by the external loads, $\Delta\delta$, Eq.(3) can be rewritten as following equation.

$$\varepsilon_t = \varepsilon_w + b\cdot\Delta\delta \geqq \varepsilon_{cr} \tag{3$'$}$$

where, b: proportional constant

$\Delta\delta$: relative root gap opening displacement

3.2.3 In case with external pulsating loads

In case that the external loads repeatedly affect on the weld metal, it is considered that ε_L in Eq.(3) is the accumulated stain in the weld metal produced by the external loads. That is,

$$\varepsilon_L = \Sigma\Delta\varepsilon_L \quad (4)$$

Here, $\Delta\varepsilon_L$ is considered to be proportional to the root gap displacement, $\Delta\delta_n$ (n = 1, 2,..., n), corresponding to the magnitude of each external load. So, ε_L can be rewritten as Eq.(5).

$$\varepsilon_L = \Sigma\Delta\varepsilon_L = \Sigma(b_n\cdot\Delta\delta_n) \quad (5)$$

where, $\Delta\varepsilon_L$: strain due to external pulsating loads

b_n (n = 1, 2,..., n) : proportional constant

$\Delta\delta_n$ (n = 1, 2,..., n) : relative root gap opening displacement due to the pulsating loads

Therefore, the Eq.(1) becomes as follows under the pulsating loads.

$$\varepsilon_t = \varepsilon_w + \varepsilon_L = \varepsilon_w + \Sigma(b_n\cdot\Delta\delta_n) \geqq \varepsilon_{cr} \quad (6)$$

By the way, in case that the external pulsating loads affect uniformly, Eq.(6) can be described as follows.

$$\varepsilon_t = \varepsilon_w + \varepsilon_L = \varepsilon_w + 2\cdot f\cdot b\cdot\Delta\delta\cdot t_i \geqq \varepsilon_{cr} \quad (6)'$$

where, f: frequency

t_i: time from the liquidus to the solidus

3.3 Critical strain for the solidification crack initiation

Trans-Varestraint cracking test is the test, by which critical strain of the solidification crack initiation, ε_{cr}, CST and BTR are obtained (see Fig.3). Here, whether ε_{cr} can be applied in case that the external pulsating loads affect is investegated. And the result of the test in which the pulsating loads affect uniformly (Fig.2) is rearranged by $\Delta\delta$ and ε_L as shown in **Fig.5**. Then, based on the deciding equation (Eq.(6)) of the solidification crack initiation under the pulsating loads, **Figure 6** shows the conceptional figure of $\Delta\delta$ and ε_{cr}.

In Fig.5, considering the relation between $\Delta\delta$ and ε_L, the solidification crack initiates with small ε_L in proportion as $\Delta\delta$ becomes large. This means that the larger $\Delta\delta$ becomes, the smaller ε_{cr} becomes (Eq.(6) and Fig.6). Because, ε_w is the free shrinkage strain of the weld metal, and is the fixed value settled only by welding condition. Considering that, ε_{cr} (the constant value) obtained by Trans-Varestraint cracking test cannot be regarded that it is critical strain of the solidification crack initiation with the external pulsating loads. That is, critical strain with the external pulsating loads, ε_{cr}', can be expressed as following equation (see Fig.6).

$$\varepsilon_{cr}' = \varepsilon_{cr} - \varepsilon_i(\Delta\delta) \quad (7)$$

where, $\varepsilon_i(\Delta\delta)$: strain depending on the change of root gap opening due to the external loads (a function of $\Delta\delta$)

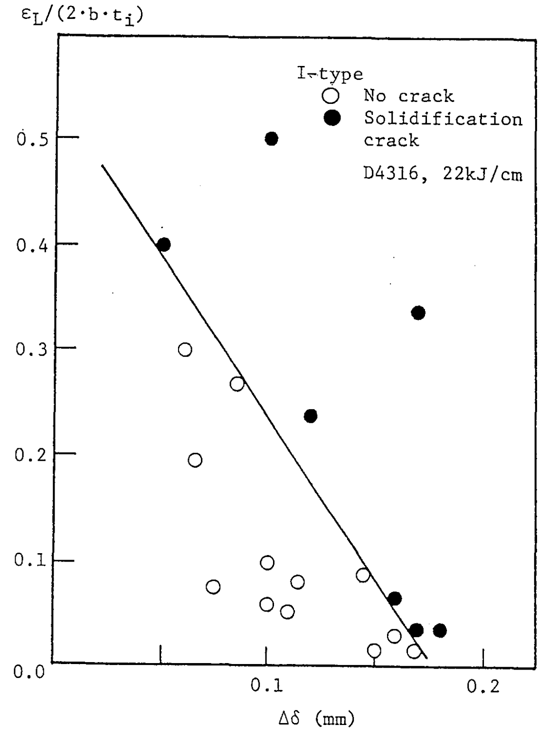


Fig.5 Relation between root gap opening displacement, $\Delta\delta$, and strain due to external loads, ε_L.

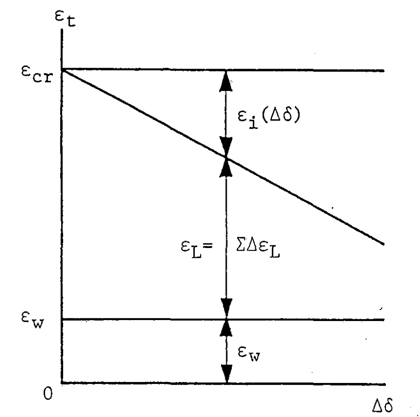


Fig.6 Critical strain, ε_{cr}, for solidification crack.

In the case that the external pulsating loads uniformly affect, Eq.(7) can be expressed as follows,

$$\varepsilon_{cr}' = \varepsilon_{cr} - a\cdot\Delta\delta \quad (7)'$$

where, a: proportional constant

Then the physical meaning of Eq.(7) is considered hereinafter.

Generally, as critical strain of the solidification crack, ε_{cr}, is material characteristics of the weld metal, it is considered to be constant which can be obtained by material composition and welding condition. From this point of view, Eq.(7) is inconsistent. On the other hand, the second term of the right part of Eq.(7) is depend upon the relative root gap opening displacement, $\Delta\delta$, under the pulsating loads. As the external pulsating loads are always applied during welding, the root gap is not fixed but continuously changeable. So, it is shown in Eq.(7) that ε_{cr} becomes seemingly small. Therefore, it is considered that the second term of the right part of Eq.(7) is the term to be moved to the left part of the equation for the solidification crack initiation, Eq.(6)′.

Consequently, the deciding equation for the solidification crack initiation under the external pulsating loads, Eqs.(6) and (6)′, is rewritten as follows. That is,

$$\varepsilon_t = \varepsilon_w + \Sigma(b_n \cdot \Delta\delta) + \varepsilon_i(\Delta\delta) \geqq \varepsilon_{cr} \quad (8)$$

In Eq.(8), in the case that the external pulsating loads are uniformly applied, Eq.(8) becomes as follows.

$$\varepsilon_t = \varepsilon_w + 2 \cdot f \cdot b \cdot \Delta\delta \cdot t_i + a \cdot \Delta\delta \geqq \varepsilon_{cr} \quad (9)$$

Eqs.(8) and (9) are the equations to evaluate whether the solidification crack initiates under the external pulsating loads or not.

4. Investigation on the Validity of Deciding Equation Newly Proposed

Non-dimensionalizing the deciding equation of the solidification crack initiation under the uniform external pulsating loads, it is rewritten as follows.

$$(A_s + B_s \cdot f) \cdot \Delta\delta \geqq 1 \quad (10)$$

where, $A_s = a/(\varepsilon_{cr} - \varepsilon_w)$

$B_s = 2bt_i/(\varepsilon_{cr} - \varepsilon_w)$

A_s and B_s are constant value which is decided by material composition of the weld metal, welding condition and stiffness of the welding joint. And A_s is the term expressing the root gap opening displacement perpendicular to welding line by the external pulsating loads. Therefore, if the root gap opening displacement does not occur, A_s is 0.

Solidification cracking test is done with changing the frequency and the amplitude of the uniform pulsating loads. So, the result of the test which is arranged by frequency, f, and the root gap opening displacement, $\Delta\delta$, is shown in Fig.2 by a symbol. In Fig.2, applying $\Delta\delta$ decided from two point, f = 1 and 8 (Hz), the constant A_s and B_s can be obtained as the following values.

H-type slit specimen $(1.3 + 0.9 \cdot f) \cdot \Delta\delta \geqq 1$ (11)

I-type slit specimen $(5.7 + 1.8 \cdot f) \cdot \Delta\delta \geqq 1$ (12)

The relation between f and $\Delta\delta$ obtained from Eqs.(11) and (12) is expressed by the solid line in Fig.2. Whether the crack initiates or not can be acculately evaluated from Eqs.(11) and (12).

Moreover, comparing the constant A_s and B_s in Eqs.(11) and (12), the constant, A_s and B_s, of I-type slit specimen becomes larger than that of H-type one in spite of the same welding condition and material. This is considered to be due to the difference of the in-plane stiffness. So, showing the restraint intensity of the uniform loads, R_p[5], on a horizontal axis, and the constant A_s and B_s corresponding to each specimen on vartical axis as a parameter of the in-plane stiffness (**Fig.7**), it is known that the difference of the in-plane stiffness largely influences on the solidification crack under the external pulsating loads.

Next, applying Eq.(10) on the results of another test using D4316, that is, affecting the uniform external pulsating loads at butt welding[6] and fillet welding[7], the validity of them is investigated.

First, the butt welding is investigated.

Arranging the results of Ref.6), it is necessary that stiffness of in-plane, R_p, is coincide. And predicting it, R_p becomes about 25kN/mm·mm. Therefore, obtaining the constant A_s and B_s from Fig.7, they are 1.1 and 0.8 respectively and the deciding equation of the solidifiction crack initiation becomes as follows.

$$(1.1 + 0.8 \cdot f) \cdot \Delta\delta \geqq 1 \quad (13)$$

The result obtained from Eq.(13) is shown by the solid line in **Fig.8 (a)**.

Secondly, using Eq.(10), the results of the fillet welding are arranged[7].

In the case that the uniform external pulsating loads are applied on the weld line in fillet welding, the root gap does not change. So, the first term of the left part of Eq.(10) becomes $A_s = 0$. Obtaining B_s with $A_s = 0$ from

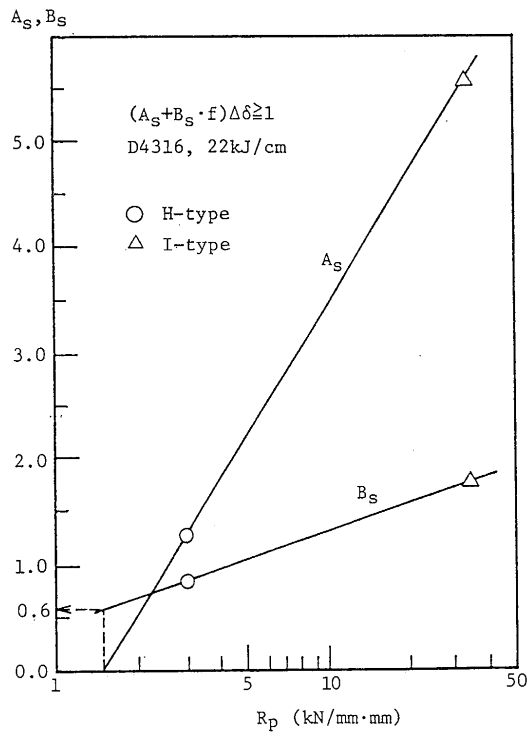


Fig.7 Relation between restraint intensity, R_p, and constant values, A_s, B_s.

Fig.7, B_s is 0.6. Then, in fillet welding, vartical strain, ε, is not applied, but shearing strain, γ, is applied. Therefore, it is necessary to substitute γ for ε. Based on the equation of yield condition by Von Mises, substituting γ when the pure shearing stress is applied for ε when tensile stress of uni-axis is a pplied, γ becomes $1.50 \times \varepsilon$ and $\Delta\delta$ becomes $0.67 \times \Delta\delta_H$. In this case, the deciding equation of the solidification crack initiation is the next one.

$$0.4 \cdot f \cdot \Delta\delta_H \geqq 1 \qquad (14)$$

where, $\Delta\delta_H$: the relative root gap opening displacement in the weld line direction

The result obtained from Eq.(14) is shown in **Fig.8(b)**.

As mentioned above, it is elucidated that the valid result can be obtained from the deciding equations of the solidification crack initiation under the pulsating loads proposed in this paper.

5. Conclusion

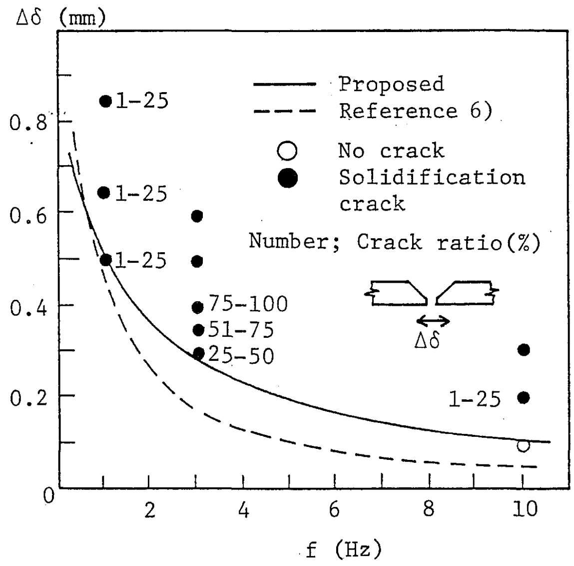
In this study, the weld cracking test under the pulsating loads was carried out and was investigated based on welding mechanics. A deciding measure for the solidification crack produced in the weld metal and evaluating method by using it were proposed. The obtained main results are as follows.

(1) Under the pulsating loads, there is a possibility which the solidification crack initiates in the zone, where no solidification crack initiates from Trans-Varestraint cracking test. Therefore, deciding the solidification crack initiation under the pulsating loads from the resluts of Trans-Varestraint cracking test, the accuracy of evaluation is low.

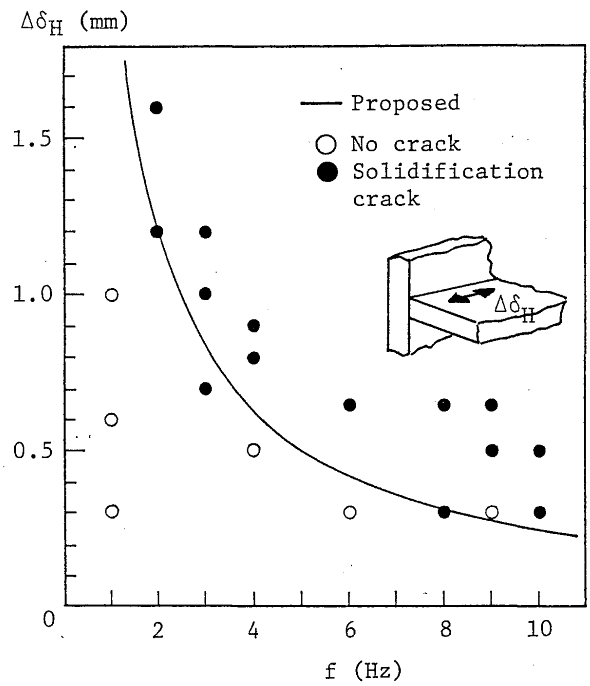
(2) The accumulation strain, ε_t, by which the weld metal was repeatedly applied at a short time from the liquidus to the solidus was proposed as a measure for deciding the solidification crack initiation under the pulsating loads. The solidification crack initiates when ε_t is larger than critical strain, ε_{cr}, which is the materials characterisation.

(3) ε_t was expressed with the relative root gap opening displacement, $\Delta\delta$, which can be easily measured before welding. Moreover, the practical deciding equation for solidification crack initiation under the pulsating loads using $\Delta\delta$ was derived.

(4) For the case that the uniform pulsating loads are applied, the validity of the practical deciding equation was concretely shown.



(a) butt weld joint



(b) fillet weld joint

Fig.8 Applicability of proposed equation for solidification crack.

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