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| Title | The Local Approach to Fracture Strength Evaluation of Welded Joints |
| Author(s) | Minami, Fumiyoshi |
| Citation | Transactions of JWRI. 1996, 25(2), p. 89-108 |
| Version Type | VoR |
| URL | https://doi.org/10.18910/7670 |
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The Local Approach to Fracture Strength Evaluation of Welded Joints

by Fumiyoshi MINAMI*

* Dept. Welding & Production Engineering, Osaka University
Suita, Osaka, Japan

Abstract

Fracture mechanics test results for welded joints should be handled with attention to the mechanical and metallurgical inhomogeneity in welds. This paper develops the procedure for fracture strength evaluation of welded joints based on the Local approach. The Weibull stress, consisting of a local stress in a specific region responsible for fracture initiation, was employed as a fracture driving force for welds. It was demonstrated that the critical Weibull stress at fracture initiation is independent of the strength mis-match condition near the notch tip. Transferability of fracture toughness results to fracture performance evaluation of welded joints was also confirmed through the analysis of the Weibull stress. As a new assertion, fracture toughness requirement based on the Local approach has been proposed. This is characterized by the equivalent CTOD concept, which provides a compatible Weibull stress between the toughness specimen and the structural component. The new procedure quantifies the fracture toughness requirement to meet a design solution of the structural component.

1. Introduction

Fracture mechanics tests of welded joints are increasingly conducted for weldments of high strength steels where the structural integrity against brittle fracture is of the greatest concern. The purpose of the tests is to clarify toughness properties of materials for use in connection with the welding condition and to evaluate the fracture tolerance of weldments under the service condition. However, attention should be focused to the heterogeneous nature of welds. For instance, toughness results for the heat affected zone (HAZ) are sensitive to the notch tip location in welds. Once the notch tip hits the local brittle zone (LBZ) in the HAZ,

considerably low toughness value would be observed. The identification of microstructure sampled by the notch tip, in particular at fracture initiation point is required to understand the real meaning of the test results. Several guidelines¹⁻⁶⁾ are presented with respect to the recommended procedure for fracture toughness testing of weldments. To the extent that the metallurgical heterogeneity causes complicate fracture behavior to be examined, the mechanical heterogeneity imposes a complex problem in the fracture strength evaluation of weldments. A number of recent studies⁷⁻¹²⁾ have addressed the significance of strength mis-matching between the base and weld metals. Not only the deformation behavior but the fracture resistance

of welded joints is affected to a large extent by the strength mis-matching. The engineering characterization of fracture performance of weldments is required as a function of definite parameters which represent the heterogeneity of welds.

It is also of great importance to quantify the interaction between the required fracture toughness of materials and the structural integrity of weldments. A common engineering approach to fracture performance assessment of structural components is the use of the CTOD design curve^{13, 14}), the relationship between the crack tip opening displacement (CTOD) and the applied strain. The structural component is supposed to fail at the same CTOD level as the critical CTOD measured in the fracture toughness test. However, it is pointed out elsewhere that the direct application of toughness results yields conservative evaluation of the structural performance. This is due to the difference in the geometrical constraint between the toughness specimen and the structural component. Recently two progressive methods have been proposed to address the specimen geometry effect on the fracture resistance. One is the two-parameter approach, so-called *J-T* and *J-Q* theories¹⁵⁻¹⁹), where *T*-stress and *Q*-parameter were developed as the near-crack tip constraint parameter. Attempts were done using *T*-stress and *Q*-parameter to estimate the constraint effect on the fracture toughness. Nevertheless, there remain rooms for improvement of the estimation procedure²⁰). Another method is the Local approach^{21, 22}) introducing the Weibull stress σ_w as an alternative fracture driving force. The Weibull stress σ_w was derived from the weakest link formulation of cleavage fracture taking account of near-crack tip stress fields. According to the Local approach, the critical Weibull stress $\sigma_{w,cr}$ at fracture obeys the two-parameter Weibull distribution independent of the size and geometry of test specimens used.

This paper employs the Local approach to quantify the fracture resistance of heterogeneous welds. Firstly the HAZ CTOD test results were critically reviewed with focus on the significance of the LBZ and the strength mis-matching between the base and weld metals. It is exhibited that the HAZ toughness depends on the size of the LBZ sampled by the notch tip as well as the mis-match condition in welds. In

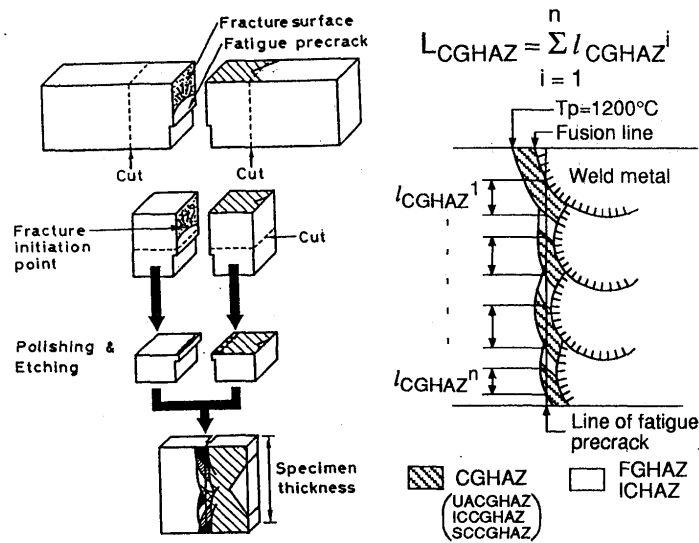
order to include such characteristics in fracture resistance evaluation of weldments, the Weibull stress for welds was defined as the integration of a local stress over a specific region responsible for fracture initiation. The advantage of the Local approach was demonstrated through (a) the prediction of strength mis-match effect on fracture toughness results, and (b) the transferability analysis of toughness results to fracture performance assessment of welded joints. An extended discussion was followed as to a reasonable fracture toughness requirement to meet the design solution of structural components.

2. Effect of Heterogeneity on Fracture Resistance of Welded Joints

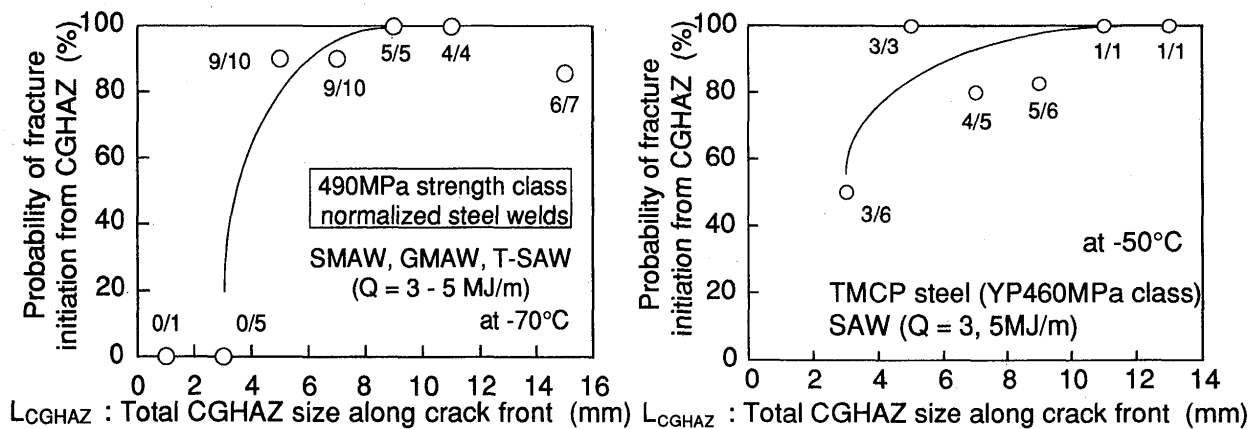
2.1 Effect of metallurgical heterogeneity- Local brittle zone

In the last decade, the significance of local brittle zone (LBZ) in multi-pass welds was discussed energetically for the use of high-grade high strength steels (TMCP steels) for offshore structures. The HAZ toughness of high-grade steels is generally quite superior compared to that of conventional steels, but surprisingly low toughness value is occasionally observed if the notch tip of the test specimen hits a particular region in the HAZ. Studies²³⁻²⁵) using simulated HAZ CTOD test revealed that the coarse grained HAZ (CGHAZ), in particular intercritically reheated CGHAZ (ICCGHAZ) corresponds to the LBZ in 490MPa class high strength steel welds. The toughness embrittlement of the ICCGHAZ is associated with the formation of brittle microstructures, high-carbon martensitic islands (M-A constituents). It was also exhibited that the ICCGHAZ toughness may be recovered by reheating effects of succeeding weld passes, although the degree of toughness improvement depends on alloying elements²³⁻²⁵).

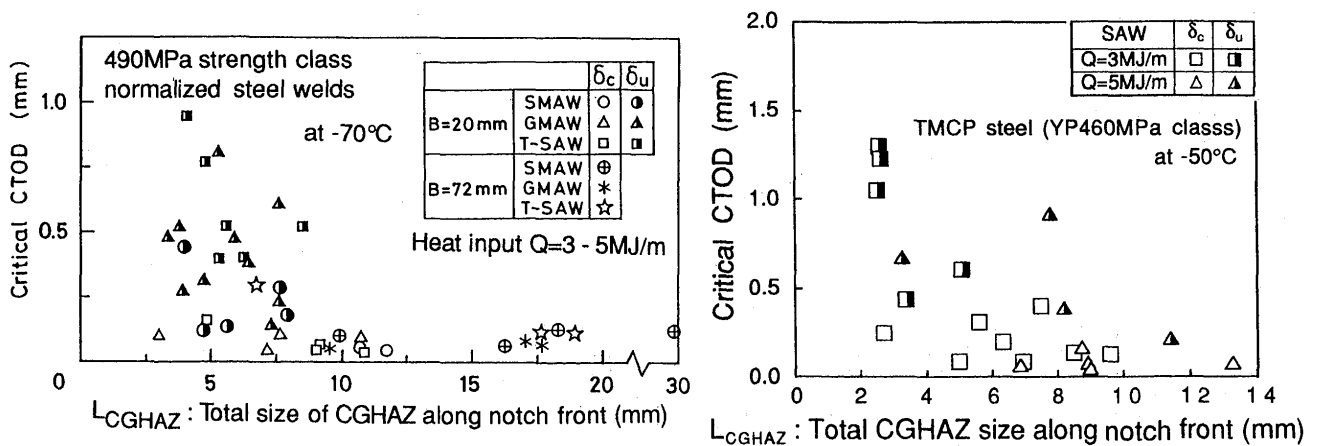
In actual welded joints, the distribution of HAZ microstructures is much complicated. For the pre-qualification test purpose²), the specimen with a through-thickness notch along the straight fusion line of K-groove welds is recommended to use for larger sampling of the LBZ along the notch front. Even for such a case, fracture toughness test results depend on the notch location in welds. Figure 1 dem-



(a) Sectioning procedure for identification of microstructures along notch front and the definition of CGHAZ size L_{CGHAZ} along notch front.



(b) Influence of CGHAZ size L_{CGHAZ} on probability of brittle fracture initiation from CGHAZ.



(c) Influence of CGHAZ size L_{CGHAZ} on critical CTOD at brittle fracture.

Fig. 1 Fracture toughness test results for HAZ-notched specimens arranged with CGHAZ size along crack front. (δ_u and δ_c : Critical CTODs at brittle fracture with and without stable crack growth larger than 0.2mm, respectively)

Table 1 Classification of HAZ microstructure of multi-pass welds according to peak temperature of weld thermal cycle.

| Peak temperature by first cycle | Peak temperature by subsequent cycles | HAZ-microstructure |
|---------------------------------|---------------------------------------|--------------------|
| Melting point ~ 1200°C (CGHAZ) | Melting point ~ 1200°C | UACGHAZ |
| | 1200 ~ 850°C | FGHAZ |
| | 850 ~ 750°C | ICCGHAZ |
| | 750 ~ 450°C | SCCGHAZ |
| 1200 ~ 850°C (FGHAZ) | 450 ~ | UACGHAZ |
| | Melting point ~ 1200°C | UACGHAZ |
| | 1200 ~ 850°C | FGHAZ |
| | 850 ~ 750°C | ICHAZ |
| 850 ~ 750°C (ICHAZ) | 750 ~ | FGHAZ |
| | Melting point ~ 1200°C | UACGHAZ |
| | 1200 ~ 850°C | FGHAZ |
| | 850 ~ | ICHAZ |

onstrates the HAZ-notched test results using three-point bend specimens for a normalized steel of 490MPa strength class²⁶⁾ and a TMCP steel with 460MPa class yield strength²⁷⁾. The test results are arranged with the total size L_{OGHAZ} of the unaltered CGHAZ (UACGHAZ), ICCGHAZ and subcritically reheated CGHAZ (SCCGHAZ) sampled by the notch front (see Fig. 1 (a)). These CGHAZ regions were treated as the potential LBZs in the light of their low-toughness property. Table 1 gives the definition of the HAZ microstructure used for the multi-pass welds of the TMCP steel²⁸⁾. For the normalized steel welds, a similar definition was used. It can be seen from Fig. 1 (b) that brittle fracture is initiated from the CGHAZ in almost all specimens except for the case of small sampling of the CGHAZ. In this sense, test results of through-thickness notched specimens reflect the toughness level of the CGHAZ itself. However, as exhibited in Fig. 1 (c), the critical CTOD value at fracture initiation depends on the CGHAZ size L_{OGHAZ} . It is pointed out elsewhere^{24, 29-31)} that the critical CTOD value of the HAZ-notched specimen is generally decreased with increasing the size of the CGHAZ sampled by the notch front. Nevertheless we should be reminded that the lower bound toughness of the specimen with less amount of the CGHAZ is almost identical with the toughness level of the specimen with a large amount of the CGHAZ. This suggests that HAZ toughness test results have a statistical aspect.

2.2 Effect of mechanical heterogeneity- Strength mis-matching in welds

Fracture toughness test results for the HAZ are also affected by strength mis-matching between the base and weld metals. An implicit understanding commonly applied in the welding material selection is the use of overmatched weld metals in terms of the yield strength. However, it has recently been pointed out that strength overmatching of the weld metal is not always beneficial from the viewpoint of HAZ fracture resistance. The followings are the review of the strength mis-match effect on the CTOD test results for the HAZ.

Welded joints tested were TMCP high strength steel welds²⁷⁾, mild steel welds³²⁾, HT780 steel welds^{33, 34)} and StE 460 steel welds³⁵⁾. In each welded joint, a certain heat input was applied using the same welding process with different weld metals. Hence the metallurgical property of each HAZ is expected to be independent of the mis-match condition in welds. Table 2 lists the mechanical properties of the base steels and weld metals. The range of yield strength ratio (Sr)Y between the base and weld metals was 0.5 to 2.5. Figure 2 shows the geometry of test specimens used. Each specimen has a notch tip in the HAZ adjacent to the weld fusion line. CTOD tests were conducted at a certain temperature in the brittle-to-ductile transition temperature range for each welded joint. CTOD values for the bend specimens extracted from the TMCP steel welds, mild steel welds and HT780 steel welds were calculated in accordance with BS5762³⁶⁾. With respect to the StE 460 steel welds, the CTOD was measured directly with δ_5 clip³⁷⁾ mounted on the specimen's side surface at the original fatigue crack tip over a gage length of 5mm. For the tension specimen taken from the HT780 steel welds, the Dugdale model³⁸⁾ was used.

Figure 3 summarizes the CTOD results as a function of the yield strength ratio (Sr)Y. It is found in each welded joint that the critical CTOD value for the HAZ depends significantly on the strength ratio (Sr)Y. The increase in (Sr)Y results in smaller critical CTOD value on the average. Two plausible interpretations are considered of the strength mis-match effect on the HAZ CTOD results. (1)

Table 2 Mechanical properties of base and weld metals of welded joints with strength mis-matching.

| | | Heat input (MJ/m) | Mechanical properties | | | | | | | |
|---------------------|-----------------|-------------------|-----------------------|------------------|--------|------------------|---------------------------|------------------|---------------------------|--------|
| | | | Base metal | | | Weld metal | | | | |
| | | | σ_Y (MPa) | σ_T (MPa) | YR (%) | σ_Y (MPa) | σ_Y^W / σ_Y^B | σ_T (MPa) | σ_T^W / σ_T^B | YR (%) |
| TMCP steel welds | Even | Q = 3.0 | 440 | 549 | 80.1 | 481 | 1.09 | 563 | 1.03 | 85.4 |
| | Over | | | | | 581 | 1.32 | 647 | 1.18 | 89.8 |
| Mild steel welds | Over (Joint I) | Q = 4.2 | 305 | 438 | 69.6 | 758 | 2.49 | 861 | 1.97 | 88.0 |
| | Over (Joint II) | | | | | 468 | 1.53 | 573 | 1.31 | 81.7 |
| HT780 steel welds | Even | Q = 3.6 | 789 | 845 | 93.4 | 711 | 0.90 | 929 | 1.10 | 76.5 |
| | Under | | | | | 336 | 0.43 | 422 | 0.50 | 79.6 |
| StE 460 steel welds | Even | Q = 2.9 | 458 | 625 | 73.3 | 620 | 1.35 | 770 | 1.23 | 80.5 |
| | Under | | | | | 248 | 0.54 | 540 | 0.86 | 45.9 |
| | Over | | | | | 964 | 2.10 | 1230 | 1.97 | 78.4 |

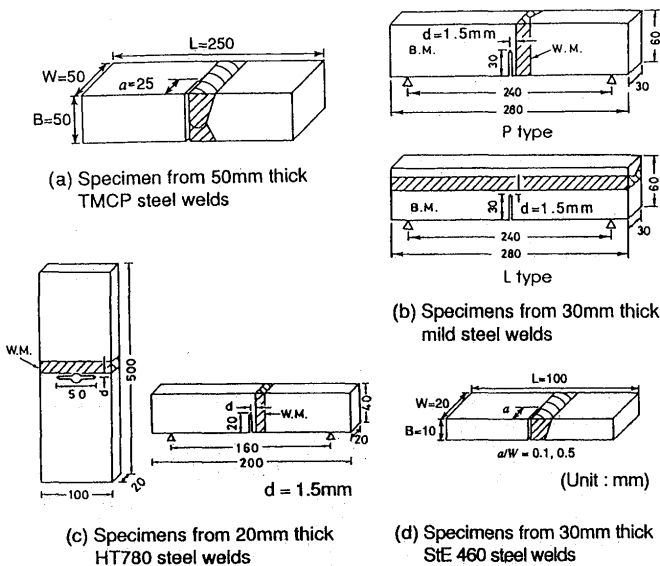


Fig. 2 Configurations of CTOD specimens with a notch in HAZ.

Inappropriate evaluation of the CTOD : Asymmetrical crack opening caused by mechanical heterogeneity should be taken into account in the evaluation of the CTOD. (2) The constraint effect of the overmatched weld metal on the HAZ toughness.

Figure 4 rearranges the CTOD results by using the local CTOD^{33, 34)}, which was defined as the local opening component on the base metal side. The local CTOD was evaluated by FE-analysis. With respect to the TMCP steel welds the critical CTOD values were converted by the weakest link model³¹⁾ to

| TMCP steel welds | Mild steel welds | | HT780 steel welds | | StE 460 steel welds | |
|------------------|------------------|--------|-------------------|---------|---------------------|-----------|
| | P type | L type | Bend | Tension | a/W = 0.1 | a/W = 0.5 |
| ○ | △ | ▲ | □ | ■ | ◇ | ◆ |

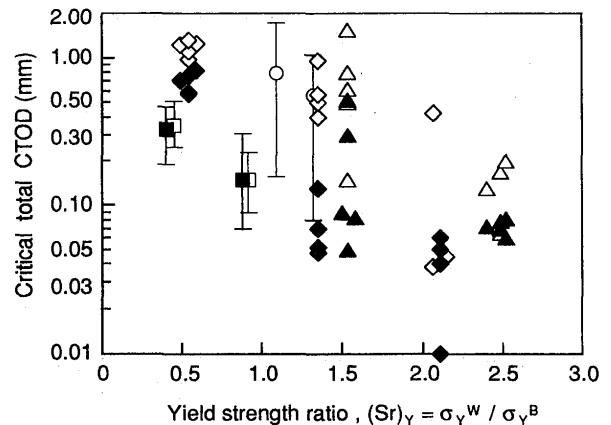
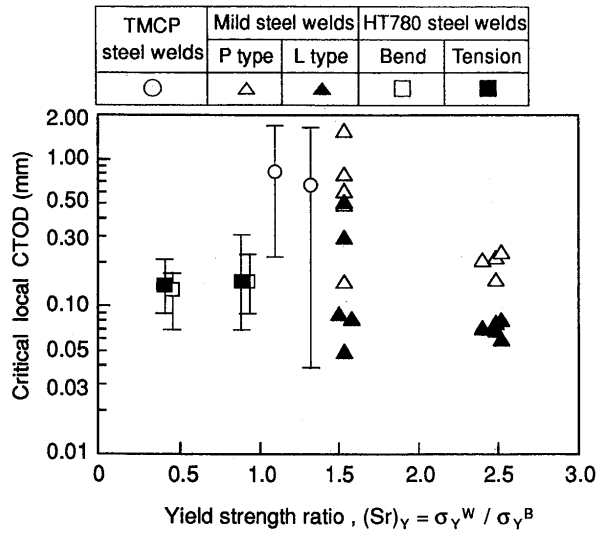


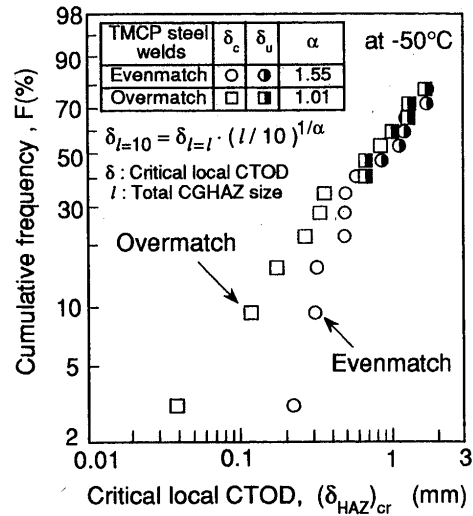
Fig. 3 Effect of yield strength ratio on critical CTOD of HAZ-notched specimens

those for specimens with the CGHAZ size $L_{OGHAZ} = 10\text{mm}$, because the evenmatched and overmatched specimens were differ in L_{OGHAZ} . Looking on the HT780 steel welds, the critical local CTOD of the undermatched specimen is much the same with the evenmatched specimen. In the mild steel welds and TMCP steel welds, however, the overmatched specimens still give lower critical CTOD than the evenmatched specimens. This can be explained in terms of the constraint effect of the overmatched weld metal on the local stress in the HAZ. Figure 5 demonstrates the numerical result²⁷⁾ by 3D

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(a) Effect of yield strength ratio on critical local CTOD.



(b) Distribution of critical local CTOD for evenmatched and overmatched joints.

Fig. 4 CTOD test results of HAZ-notched specimens evaluated by local CTOD parameter.

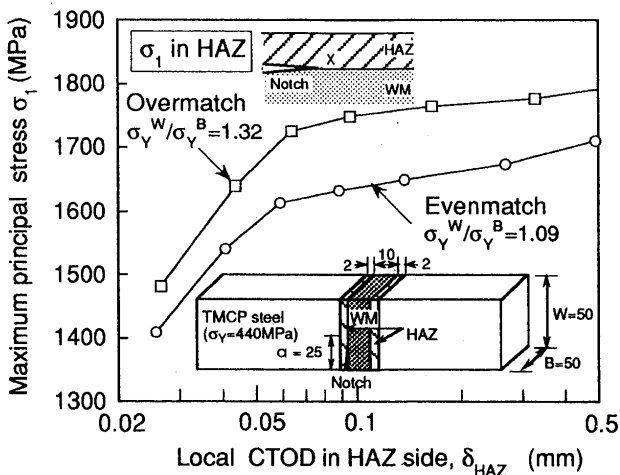


Fig. 5 Strength mis-match effect on near notch-tip stress in HAZ (3D FE-results).

FEM on the near-notch tip stress in the HAZ. The CTOD specimen extracted from the TMCP steel welds was analyzed with a model having a notch at the HAZ/WM boundary. It can be seen that the overmatch condition elevates the maximum principal stress in the HAZ, which facilitates brittle fracture initiation in the overmatched specimen at a lower CTOD level. Similar results were observed in the parametric analysis of stress fields in the HAZ of mismatched welds^{27, 39}).

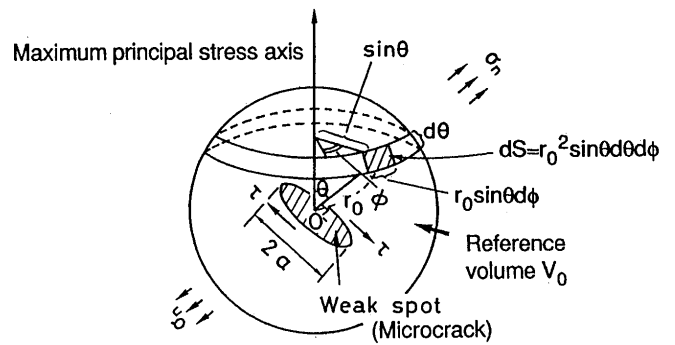


Fig. 6 Stress components for microcrack under multi-axial stress state used for Local approach.

3. Procedure of Local Approach to Cleavage Fracture of Welded Joints

As indicated, the heterogeneity in welds plays an important role in fracture behavior of welded joints: (1) A specific region with reduced toughness controls the initiation of brittle fracture. (2) Strength mis-matching exerts a marked influence on the stress field in welds. These properties force us to think out alternative procedure for fracture strength evaluation of welded joints. This paper applies the Local approach to cleavage fracture of weldments.

The Local approach^{21, 22}) was born from the characterization of statistical behavior of toughness results for ferritic materials. The

fracture resistance of the material is assumed to be determined by the weakest strength of microcracks included in the material. The instability of the microcrack is related to a local stress field near the notch tip. Such characterization of the local instability led to a new fracture driving force, the Weibull stress σ_w in the form

$$\sigma_w = \left[\frac{1}{V_0} \int_{V_f} [\sigma_{eff}]^m dV_f \right]^{1/m} \quad (1)$$

where σ_{eff} is an effective stress in a small volume dV_f in the fracture process zone, m is the Weibull shape parameter for the material, and V_0 and V_f are a reference volume defined in the Local approach and the volume of the fracture process zone, respectively. The m -value reflects the distribution of microcracks for the material. It has been shown^{21, 40-43}) that the range of the m -value for structural steels is 10 to 30. The reference volume V_0 does not affect the m -value. Besides V_0 does not disturb the transferability analysis of fracture mechanics test results. Accordingly, a unit volume is convenient to V_0 for calculating the Weibull stress⁴²). The fracture process zone V_f almost corresponds to the plastic region near the notch tip⁴²). In the engineering evaluation, the maximum principal stress can be employed as the effective stress σ_{eff} . An advanced form of σ_{eff} ⁴⁴) considering combined effects of the multiaxial stress state and a spatial distribution of microcracks is

$$\sigma_{eff} = \left[\frac{1}{2\pi} \int_0^\pi \int_0^\pi \left[\sigma_n^2 + \frac{4}{(2-\nu)^2} \tau^2 \right]^{m/2} \sin \alpha \theta d\theta d\varphi \right]^{1/m} \quad (2)$$

where the angles θ and φ define the orientation of the microcrack to the principal stress axes and the stresses σ_n and τ are the normal stress and in-plane maximum shear stress for the microcrack, respectively (see Fig. 6). The critical Weibull stress $\sigma_{w,cr}$ at brittle fracture initiation obeys the Weibull distribution with two parameters m and σ_u

$$F(\sigma_{w,cr}) = 1 - \exp \left[- \left(\frac{\sigma_{w,cr}}{\sigma_u} \right)^m \right] \quad (3)$$

which is expected to be a material property

independent of the specimen geometry and the notch size^{21, 22}). The scale parameter σ_u is associated with the toughness level of the material, the microcrack distribution and the reference volume V_0 . An excellent review⁴⁵) of the recent progress in the Local approach has been published.

For the application of the Local approach to fracture in welds, we should speculate as to the fracture process zone V_f in welds. For the specimen with a notch in the weld metal, the V_f can be taken from the weld metal region near the notch tip. On the other hand, the HAZ-notch complicates the fracture process zone significantly, because the notch tip includes several microstructures of welds. Under the circumstances that fracture initiation is controlled by the embrittled CGHAZ as exhibited in Fig. 1, the CGHAZ sampled by the notch tip can be assigned as the fracture process zone. Namely, the fracture process zone V_f in welds is confined to a specific region :

- V_f for the weld metal-notch
- : the weld metal
- V_f for the HAZ-notch
- : the CGHAZ (in the case of CGHAZ toughness controlling fracture)

It is pointed out in both cases that the stress filed in the fracture process zone can be varied with the strength mis-match condition in welds.

4. Local Approach to Strength Mis-Match Effect on Toughness Results

The Local approach was applied to cleavage fracture of mis-matched specimens. Diffusion bonded joints made with a SM490 steel and a HT780 steel were employed⁴⁶). Figure 7 shows the procedure for diffusion bonding. The SM490 and HT780 steel plates also followed the same heat treatment as given in the bonding process. The yield strength σ_Y and tensile strength σ_T of the SM490 and HT780 steels after heat treatment were $\sigma_Y=283\text{MPa}$ and $\sigma_T=472\text{MPa}$, and $\sigma_Y=533\text{MPa}$ and $\sigma_T=717\text{MPa}$, respectively. In this paper, the SM490 and HT780 steels after heat treatment were termed the materials S and H. Figure 8 exhibits the hardness distribution and microstructures in the vicinity of the bonded interface. The hardness and microstructure are abruptly changed at the bonded interface, while no significant difference can be found between the regions near the

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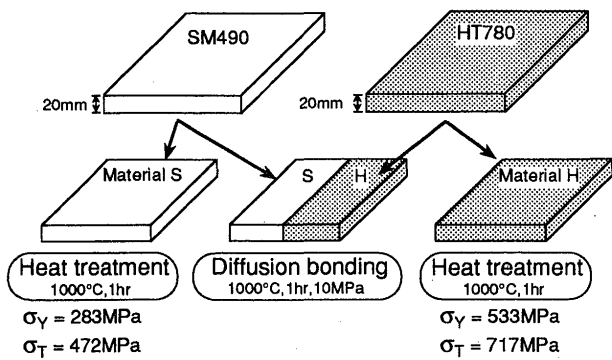


Fig. 7 Diffusion bonding and heat treatment of SM490 and HT780 steel plates.

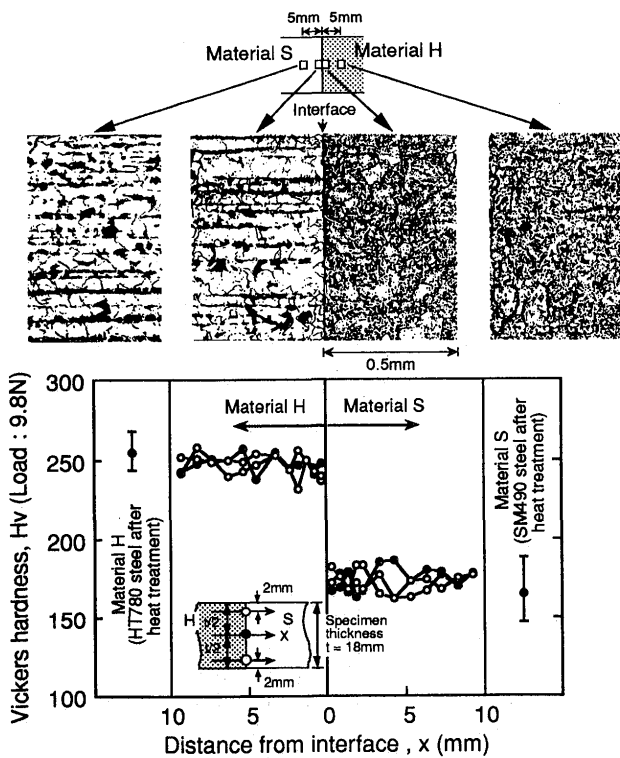


Fig. 8 Microstructures and hardness distribution near interface of diffusion bonded joints.

interface and apart from the interface. The materials S and H had the ferrite/pearlite dual phase and the austenite/martensite dual phase, respectively.

From the diffusion bonded joints and heat treated plates, 3-point bend specimens were extracted as shown in Fig. 9. In order to investigate the strength overmatch effect, the diffusion bonded specimen with a notch on the material S side is compared with the homogeneous specimen of the material S. On the other hand, the bonded specimen with a

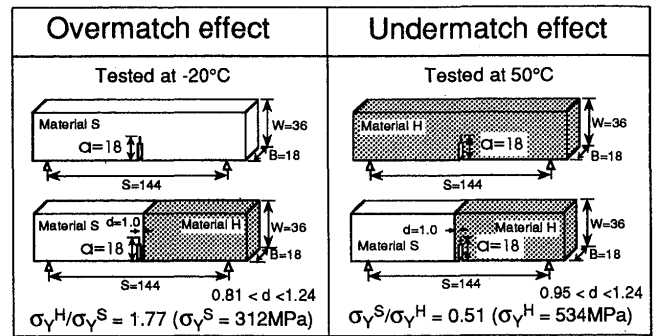
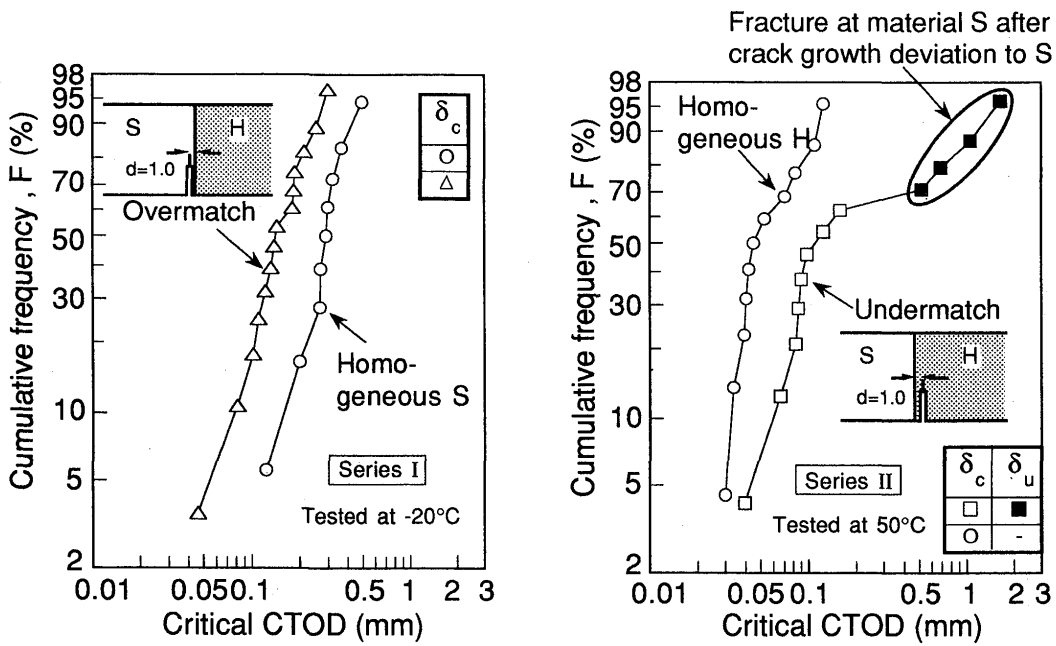


Fig. 9 Three-point bend specimens to investigate strength mis-match effect on fracture resistance.

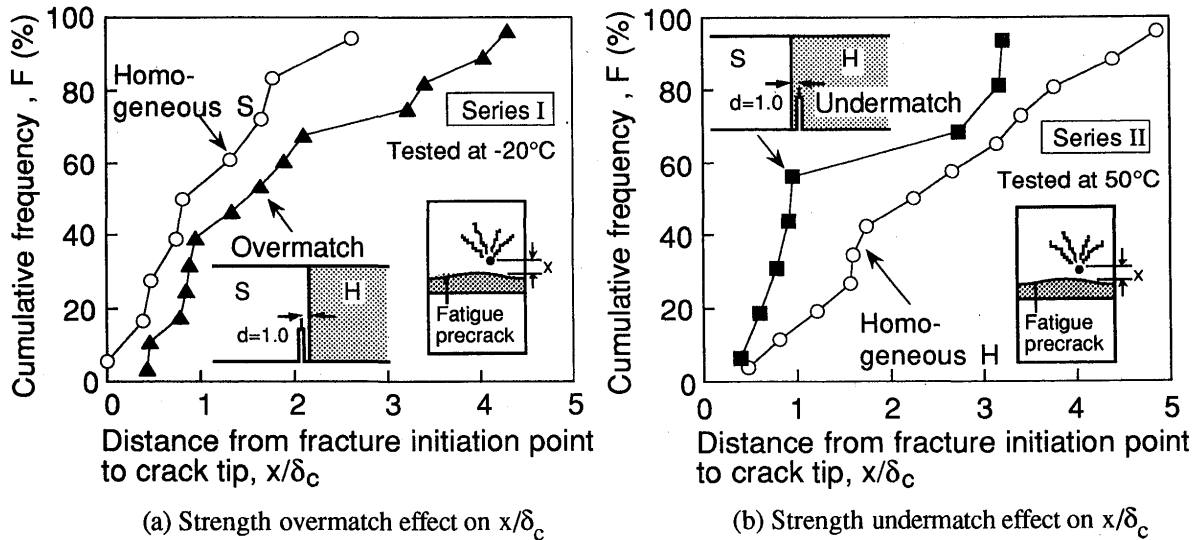
notch on the material H side and the homogeneous specimen H are used to examine the strength undermatch effect. The notch tip in the diffusion bonded specimens was located at the target distance of 1.0mm from the bonded interface. The geometry of each specimen was $B=18\text{mm}$ (specimen thickness) \times $W=36\text{mm}$ (specimen width) and the notch length a including fatigue precrack was 18mm ($a/W=0.5$). Tests were conducted at -20°C and at 50°C corresponding to a lower temperature in the ductile-brittle transition range for the materials S and H, respectively. The degree of strength mis-matching in terms of the yield strength at the test temperature was 1.77 for the overmatched specimen and 0.51 for the undermatched specimen.

Figure 10 exhibits the cumulative distribution of the critical CTOD value at brittle fracture initiation. The critical CTOD was calculated according to BS7448⁴⁷⁾. Almost all specimens failed in a brittle manner without stable crack growth larger than 0.2mm (δ_c mode), except for the undermatched specimens denoted by the symbol \blacksquare . In these undermatched specimens, brittle fracture was originated from the material S side adjacent to the bonded interface after large extension of ductile crack toward the material S. It is recognized from the test results that the fracture resistance (critical CTOD) of the material is decreased by the overmatch condition and increased by the undermatch condition. Fracture initiation point was also affected by strength mis-matching. Figure 11 gives the statistical distribution of fracture origins observed by the scanning electron microscope (SEM). The distance x from the fatigue crack tip to fracture



(a) Strength overmatch effect on critical CTOD (b) Strength undermatch effect on critical CTOD

Fig. 10 Strength mis-match effect on distribution of critical CTOD value at brittle fracture initiation.



(a) Strength overmatch effect on x/δ_c (b) Strength undermatch effect on x/δ_c

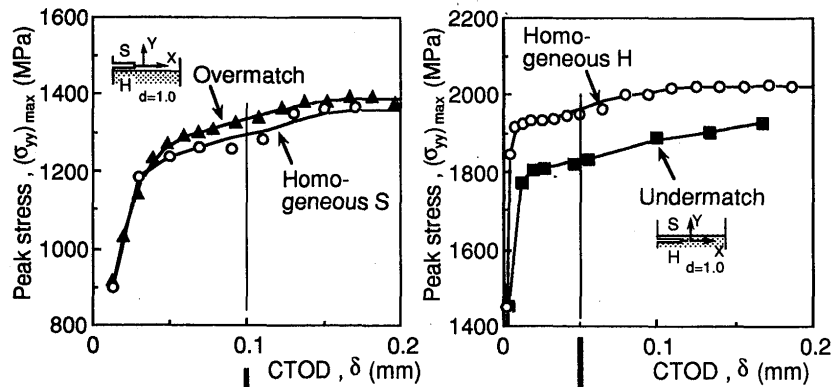
Fig. 11 Distribution of non-dimensional distance x/δ_c of fracture origins from crack tip.

origins was normalized by the critical CTOD δ_c of the specimen. The overmatched specimens have a clear tendency to contain fracture origins at a larger non-dimensional distance x/δ_c from the fatigue crack tip than the homogeneous specimens S. By contrast, in the undermatched specimens, fracture origins are closer to the crack tip.

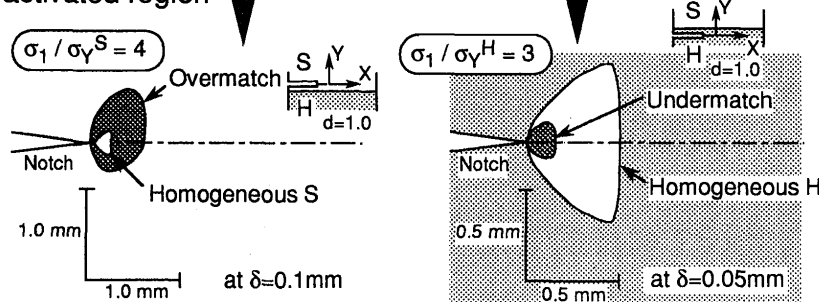
In order to evaluate the fracture toughness results of the diffusion bonded specimens, 3D FE-analysis was conducted. The

FE-code employed was JNIKE-3D supplying 8-node isoparametric elements with 8-Gaussian points. Stress-strain curves of the materials S and H obtained by round-bar tension test at -20°C and 50°C were installed in the FE-analysis. Figure 12 compares the near crack-tip stress fields between the mis-matched specimen and homogeneous specimen. The CTOD in the FE-analysis was calculated according to the same procedure as used in the experiment. It can be seen that the strength overmatch elevates

□ Near-tip peak stress $(\sigma_{yy})_{max}$



□ Extent of activated region



(a) Strength overmatch effect

(b) Strength undermatch effect

Fig. 12 Strength mis-match effect on near-tip peak stress and contour of maximum principal stress.

the near-tip peak stress, whereas the strength undermatch relaxes it. The strength undermatch effect seems to be more significant in the present specimens. Particular notice should be given to the extent of the highly stressed region near the crack tip. Contours of the maximum principal stress $\sigma_1 = 4\sigma_Y^S$ and $3\sigma_Y^H$ are drawn for the overmatched specimen and undermatched specimen, respectively, where σ_Y^S and σ_Y^H are the yield stress of the materials S and H. Compared to the result of the homogeneous specimen, the strength overmatch enlarges and undermatch reduces the stress contour remarkably. The fracture toughness results in Figs. 10 and 11 are consistent with these analytical results: The strength overmatch activated the near-tip stress field, which led to the lower critical CTOD and initiated fracture at a larger distance from the crack tip. Opposite influence was exerted in the case of strength undermatching.

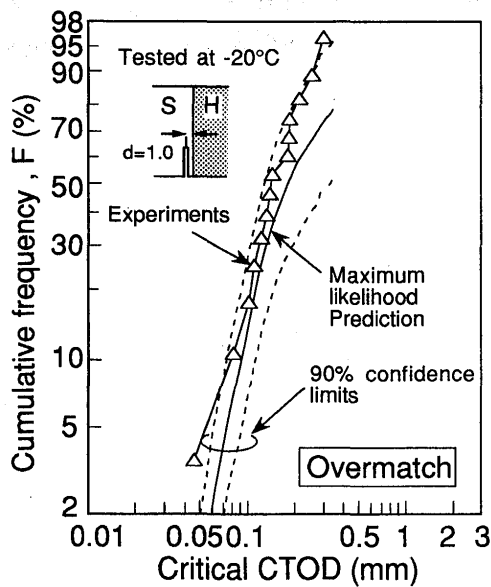
With those properties in mind, this paper applies the Local approach to fracture of mis-matched specimens. The fracture process zone V_f for the diffusion bonded specimen was

Table 3 Weibull parameters and their 90% confidence limits for homogeneous and mis-matched specimens.

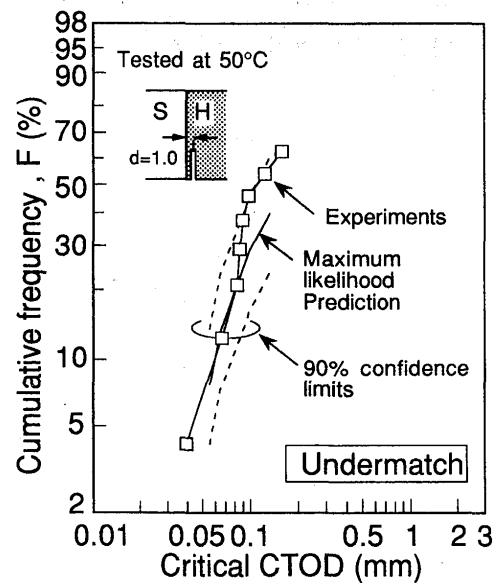
| | Maximum likelihood estimation | | 90% confidence limits | |
|--|-------------------------------|------------------|-----------------------|------------------|
| | m | σ_U (MPa) | m | σ_U (MPa) |
| Homogeneous S | 40 | 1246 | (24, 54) | (1223, 1269) |
| Bonded specimen with notch in S (Overmatch) | 31 | 1197 | (19, 41) | (1177, 1218) |
| Homogeneous H | 43 | 1773 | (25, 58) | (1748, 1799) |
| Bonded specimen with notch in H (Undermatch) | 43* | 1739* | - | - |

* Least square estimation

taken from the near-crack tip region on the notch side. With respect to the reference volume V_0 , a unit volume was adopted in this paper. The iterative procedure developed in the literature⁴²⁾ was used for the determination of the Weibull parameters m and σ_u . The integration of the effective stress σ_{eff} was performed by using the Gaussian quadrature⁴⁸⁾. Table 3 gives the maximum likelihood estimation of the Weibull parameters and their 90% confidence limits⁴⁹⁾.



(a) Prediction of strength overmatch effect



(b) Prediction of strength undermatch effect

Fig. 13 Distribution of critical CTOD value for mis-matched specimen predicted by the Local approach.

The homogeneous specimen and mis-matched specimen yielded almost the same Weibull parameters. Namely, the Weibull parameters are independent of the mis-match condition as expected from the principle of the Local approach.

On the basis of the strength mis-match independence of the Weibull parameters, the critical CTOD value of the mis-matched specimen was predicted from the toughness results of the homogeneous specimen. The necessary procedure for prediction is the linkage between the critical Weibull stress distribution for the homogeneous specimen and the Weibull stress - CTOD relationship for the mis-matched specimen calculated by FEM with the m -value of the material. Figure 13 exhibits the predicted distribution of the critical CTOD value for the overmatched and undermatched specimens. The predicted results show a good agreement with the experimental results.

5. Transferability of Toughness Results to Fracture Performance Evaluation of Weldments

The major subject of this paper is the transferability of fracture toughness test results to fracture performance evaluation of welded joints. It is widely recognized that the standard 3-point bend specimen with a deep notch generally yields a conservative evaluation of the

structural performance in a large scale yielding regime, provided conventional fracture mechanics parameters are directly used. This is attributed to the difference in the geometrical constraint between the 3-point bend specimen and the structural component. The Local approach insists that the fracture resistance of the material evaluated by the Weibull stress is independent of the geometry of fracture mechanics specimens used. In the following, the Local approach was applied to fracture of welded joints with a notch in the weld metal and in the HAZ.

5.1 Weld metal-notch

The 3-point bend test and the wide plate test with a notch in the weld metal were conducted for girth welds of a high strength pipeline steel (X80) of grade 550⁵⁰). The yield strength of the base steel was 572MPa. Welding was conducted by a mechanized GMAW with heat inputs of 0.3 to 0.9MJ/m. The welding condition applied was representative of girth welding of linepipe in the field. Undermatched, matched and overmatched weld metals were used. The overmatched welding consumable has been applied in the field practice, while the undermatched and matched consumables have not been used. The degree of strength mis-matching for the under- and overmatched joints was about

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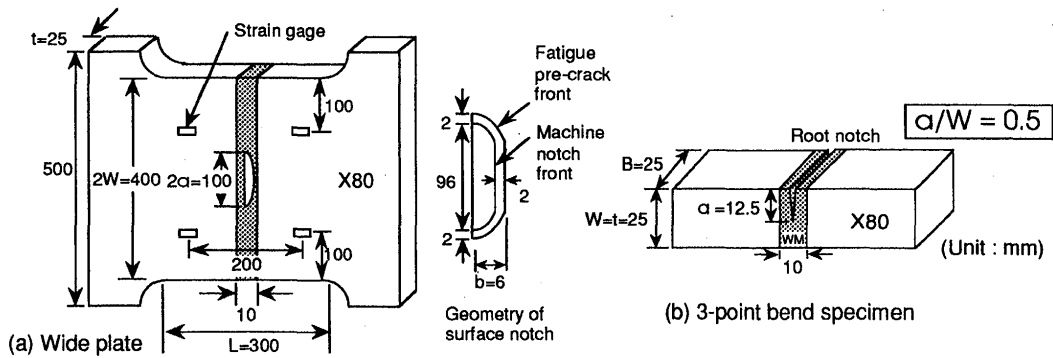


Fig. 14 Wide plate and 3-point bend specimen with a notch in weld metal.

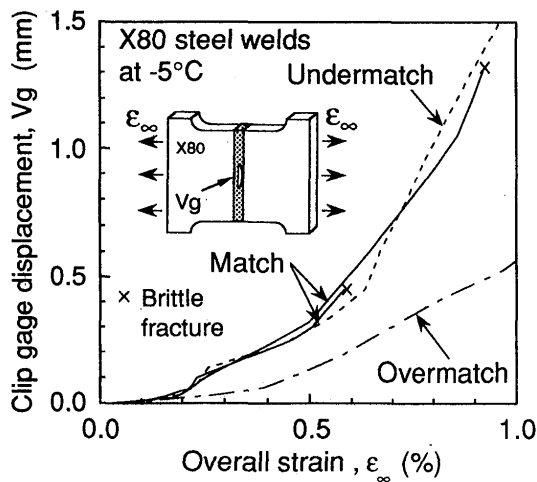


Fig. 15 Deformation behavior of wide plates with a surface notch in weld metal.

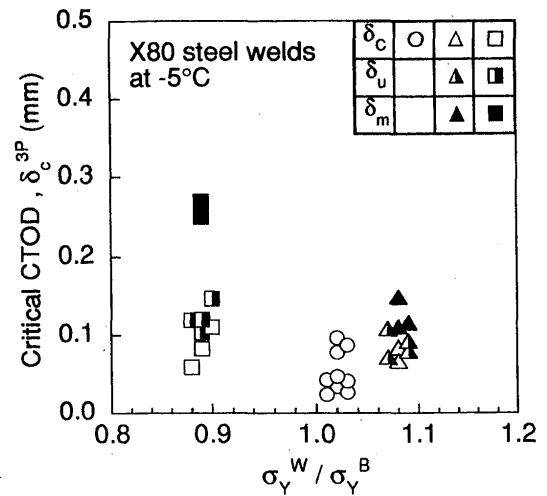


Fig. 16 CTOD test results for undermatched, matched and overmatched weld metals.

10% in terms of the yield strength ratio (S_r) Y between the base and weld metals. It is important to mention that the different electrodes were selected on the basis of the yield strength, not with respect to toughness properties.

Figure 14 shows the configuration of test specimens used. The notch was located at the center of the weld metal on the root side of welds. The wide plate was 300mm long and 400mm wide in the test section, and had a surface notch of $2a=100$ mm (length) and $b=6$ mm (depth). Fatigue precrack was introduced at the tip of the machined notch. The geometry of the 3-point bend specimen was $B=25$ mm (specimen thickness) \times $W=25$ mm (specimen width). The notch length a including fatigue precrack was 12.5 mm ($a/W=0.5$). Tests were conducted at -5°C corresponding to the minimum design temperature for buried pipelines.

Figure 15 exhibits the relationship between the notch opening displacement V_g and the overall strain ϵ_∞ for the wide plate. The V_g was measured using a clip gage mounted at the center of the notch. The overall strain ϵ_∞ was informed from the average output of strain gages attached at a distance of 100mm from the notch on both sides of the plate. The matched joint failed in a brittle manner after ductile crack growth. By contrast, unstable fracture did not occur in the under- and overmatched joints. Figure 16 presents the critical CTOD values of the 3-point bend specimens. The critical CTOD was calculated according to the British standard BS7448⁴⁷⁾. Notations δ_u and δ_c denote the CTOD at the onset of cleavage fracture with and without ductile crack growth larger than 0.2mm, respectively, and δ_m indicates the CTOD value at the maximum load plateau in the case of ductile failure. All specimens with a notch in the matched weld metal exhibited

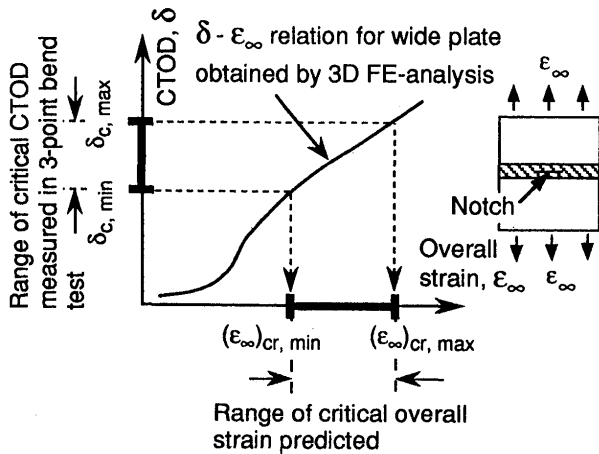


Fig. 17 Procedure for prediction of critical overall strain of wide plate from 3-point bend test results based on the conventional CTOD concept.

brittle fracture, while some extracted from the under- and overmatched joints showed ductile failure.

The present interest is the transferability of the 3-point CTOD results to fracture performance evaluation of the wide plates. In order to address this subject, 3-dimensional FE-analysis was conducted using the non-linear FE-code, JNIKE-3D. In the light of the CTOD - overall strain ϵ_{∞} relationship for the wide plate obtained by the FE-analysis, the critical overall strain $(\epsilon_{\infty})_{cr}$ of the wide plate at unstable fracture was predicted from the 3-point bend CTOD results. Figure 17 gives the procedure for prediction based on the conventional CTOD concept. The conventional CTOD concept assumes that the bend specimen and the wide plate will fracture at the same critical CTOD level. As exhibited in Fig. 18, however, this concept resulted in very conservative estimation of fracture strain of the wide plate. This is attributed to inconsistent near-tip stress fields between the bend specimen and the wide plate. At the same CTOD level, the bend specimen gives apparently higher stress and larger extent of activated region near the notch tip than the wide plate as demonstrated in Fig. 19.

On the other hand, the Local approach assumes that the bend specimen and the wide plate hold the same critical Weibull stress at fracture. In order to link the 3-point CTOD results with the wide plate fracture performance, we compute the Weibull stress σ_w - overall strain ϵ_{∞} relationship for the wide plate and the

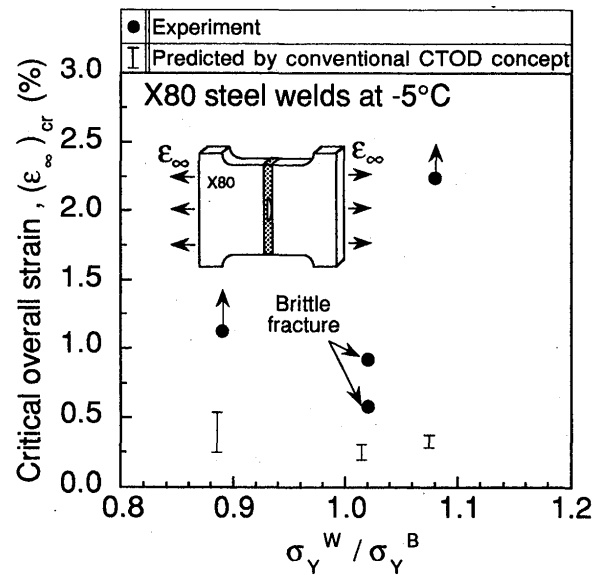


Fig. 18 Critical overall strain of wide plates measured in experiment and predicted from 3-point CTOD results by the conventional CTOD concept.

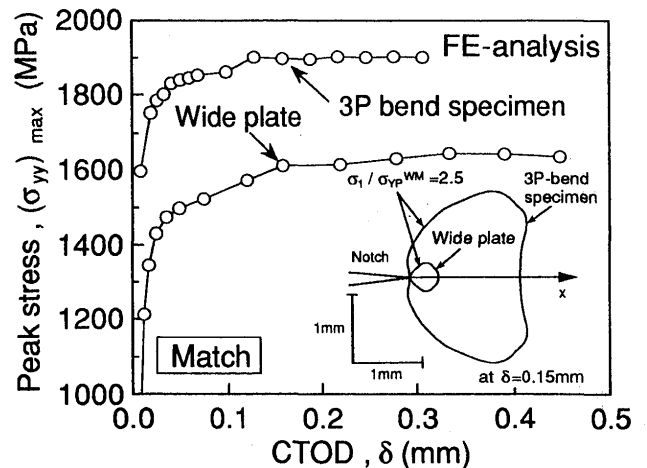


Fig. 19 Specimen geometry effect on near crack-tip stress field.

σ_w - CTOD relationship for the 3-point bend specimen as exhibited in Fig. 20⁵¹). Table 4 provides the Weibull parameters m and σ_0 for the three weld metals determined from the 3-point bend test results. In the transferability analysis, the Weibull stress for the wide plate is computed with the m -value informed from the 3-point bend specimen. By connecting the overall strain ϵ_{∞} and the critical CTOD value measured in the 3-point bend test by way of the Weibull stress, the range of the critical overall strain $(\epsilon_{\infty})_{cr}$ for the wide plate can be predicted. The predicted results are displayed in Fig. 21.

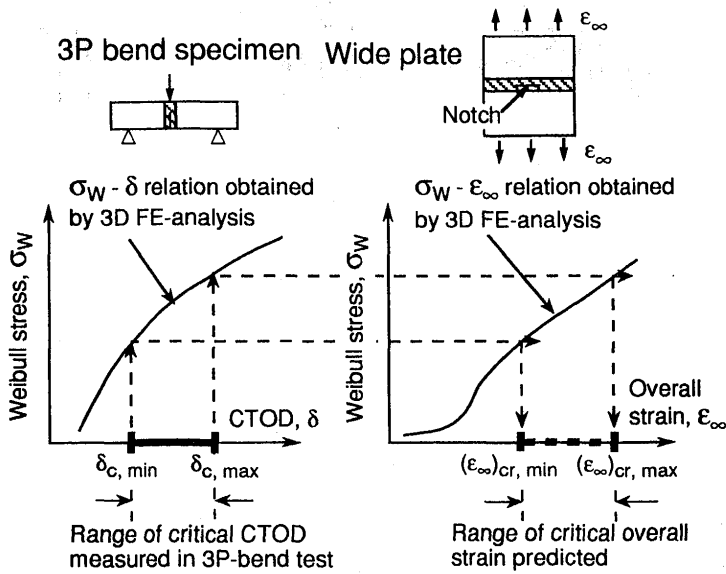


Fig. 20 Procedure for prediction of critical overall strain of wide plate from 3-point bend test results based on the equivalent CTOD concept.

Table 4 Weibull parameters for weld metals determined by most likelihood method.

| | Shape parameter m | Scale parameter σ_U (MPa) |
|------------|------------------------|-------------------------------------|
| Undermatch | 38.3 | 1591 |
| Match | 27.6 | 1683 |
| Overmatch | 33.1 | 1828 |

Compared to the conventional CTOD concept, the Local approach gives more reasonable prediction of $(\epsilon_\infty)_{cr}$ for the wide plates.

5.2 HAZ-notch

CTOD tests of the weld HAZ were conducted using the 3-point bend specimen and tension specimens with different notch depth⁵²⁾. The base steel used was a TMCP high strength steel of 460MPa yield strength class. Welding was conducted by multipass SAW with a heat input of 5MJ/m with K-groove preparation. The welded joints produced were slightly overmatched ($(\sigma_r/\sigma_y)=1.13$). Figure 22 shows the geometry of test specimens employed. The bend specimen was of standard type with the notch depth to specimen width ratio $a/W=0.5$. The tension specimens had a double-edge notch, whose depth was varied to yield different liga-

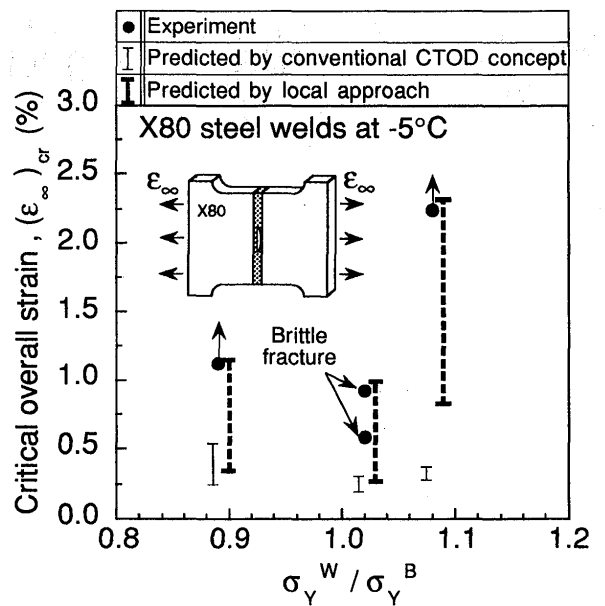


Fig. 21 Comparison between critical overall strains of wide plates predicted on the basis of the conventional CTOD concept and the equivalent CTOD concept.

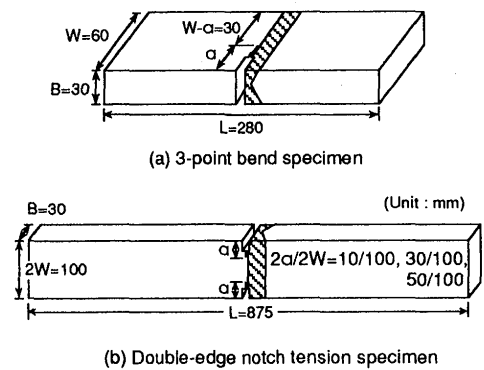


Fig. 22 Three-point bend specimen and tension specimen with a notch in HAZ.

ment size ($2a/2W=10/100, 30/100$ and $50/100$). The fatigue precrack was introduced at the tip of the machined notch in both bend and tension specimens. The notch was located along the fusion line on the straight bond side. Tests were conducted at -50°C in the transition temperature range. The CTOD value was calculated according to BS7448⁴⁷⁾ for the bend specimen and by the Dugdale model³⁸⁾ for the tension specimens. After testing, all specimens were followed by the sectioning procedure²⁾ to identify the notch tip location and the microstructure at fracture initiation. Figure 23 plots the critical CTOD values for the bend

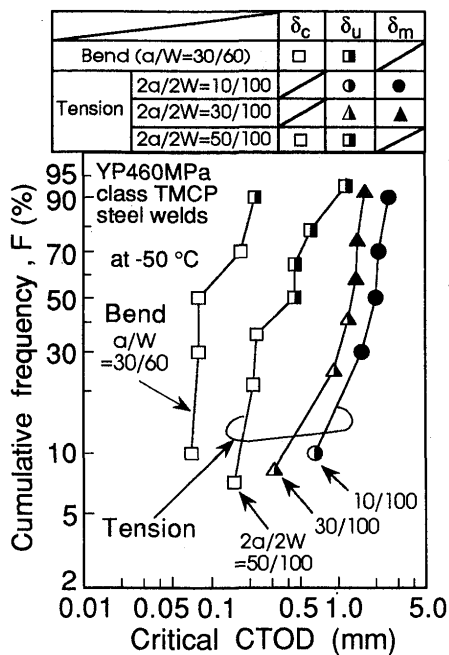


Fig. 23 Distributions of critical CTOD value for HAZ measured by 3-point bend test and tension test.

specimen and tension specimens. The tension specimens, irrespective of notch depth, present apparently larger critical CTOD value than the bend specimen. According to the sectioning, result there was no significant difference in the notch tip location in welds between the bend and tension specimens, and cleavage fracture was originated from the CGHAZ in each specimen which showed δ_c - or δ_u -mode fracture. The conservatism of the bend test results is attributed to the similar reason as discussed in Fig. 19.

The specimen geometry effect on the critical CTOD of the HAZ-notched welds was predicted by the Local approach⁵³. Figure 24 shows the the FE-model used for the Weibull stress calculation. The original CGHAZ means the HAZ region suffered from the CGHAZ thermal cycle during the welding. The mechanical properties of this region were estimated from the hardness. Since the width and the total length of the CGHAZ responsible for fracture initiation were about 1mm and 10mm, respectively, the fracture process zone was assumed as the 1×10 mm region in the original CGHAZ. The Weibull shape parameter m for the CGHAZ determined from the bend test result was 26.8. With this m -value, the distribu-

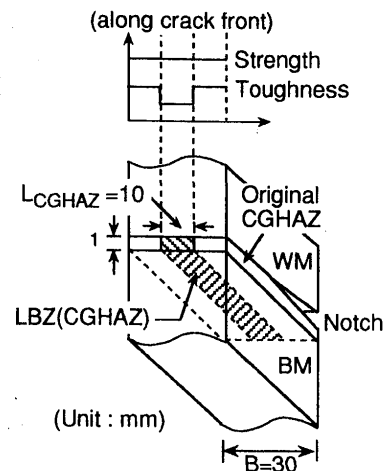


Fig. 24 FE-model including LBZ used for calculation of the Weibull stress.

tions of the critical CTOD value for the tension specimens were predicted upon the principle that the critical Weibull stress is independent of the specimen geometry. Figure 25 exhibits the predicted results. The predicted results are consistent very well with the experimental results.

6. Fracture Toughness Requirement Based on the Local Approach

The advantage of the Local approach was demonstrated through the prediction of strength mis-match effect and the transferability analysis of fracture toughness test results. As an engineering application of the Local approach, the recent study⁵¹ by authors proposed a new procedure for fracture toughness requirement. The new procedure is characterized by the equivalent CTOD concept. Figure 26 shows a key idea to link the toughness requirement with a design solution of the structural component. The assertion is that the designer should require the bend CTOD (fracture toughness) at which the equivalent Weibull stresses are built up between the bend specimen and the structural component at the design strain level ϵ_w^R . This bend CTOD is termed the equivalent CTOD.

Based on the equivalent CTOD concept, the influence of strength mis-matching on the fracture toughness requirement of welding consumables was discussed. The girth welds of the pipeline steel described in Fig.14 was considered. The design criteria employed is the

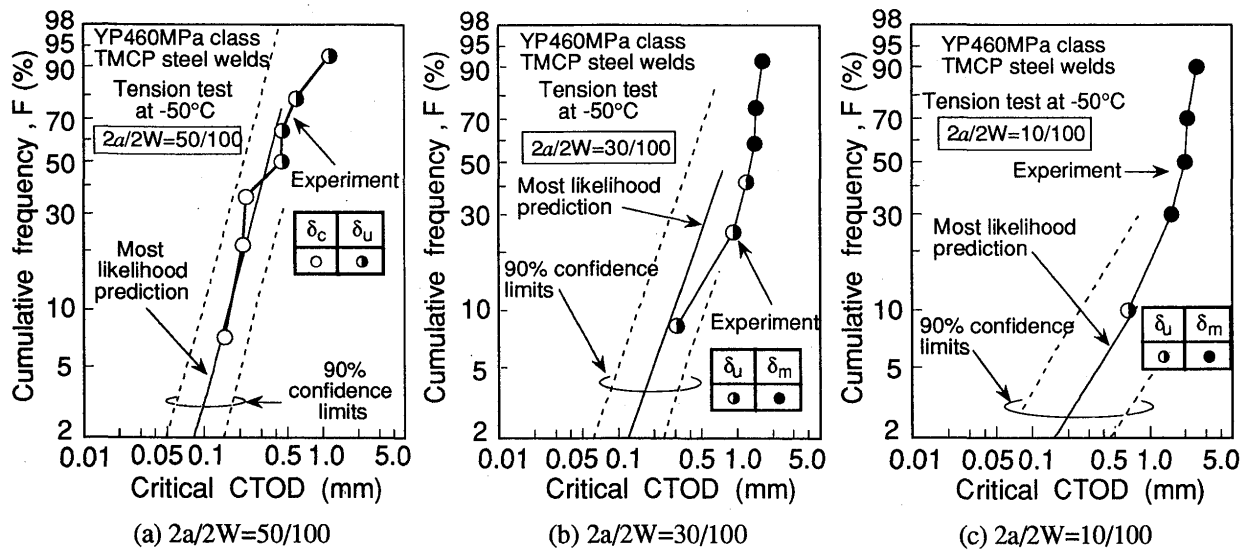


Fig. 25 Distributions of critical CTOD value for HAZ-notched tension specimens predicted from 3-point bend test results based on the local approach.

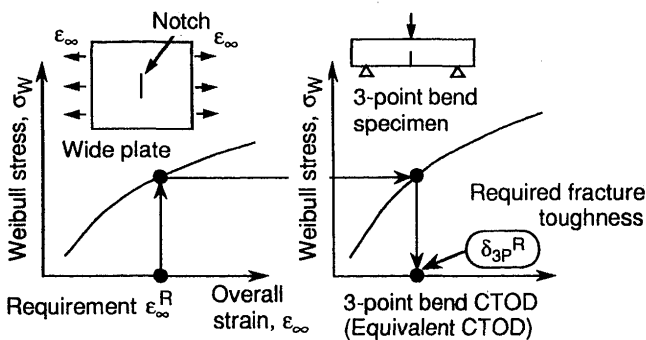


Fig. 26 Procedure based on the equivalent CTOD concept for determination of required fracture toughness to meet design solution of structural component.

deformability in terms of the overall strain $\epsilon_{\infty}^R=0.5\%$, which is commonly used at the construction of buried pipelines. Figure 27 exhibits the result of a numerical simulation of toughness requirement to meet $\epsilon_{\infty}^R=0.5\%$. The girth welds were assumed to contain a surface crack in the weld metal. Two plate thicknesses were considered for a given surface crack size. The bend specimen had a square section, B (specimen thickness)= W (specimen width) which was equal to the plate thickness t . It can be seen that the required bend CTOD δ_{3P}^R and wide plate CTOD δ_{WP}^R to meet the requirement ϵ_{∞}^R are a function of strength mis-matching, although the δ_{3P}^R seems to be less sensitive to the mis-match condition. The important result in Fig. 27 is that the level of the required

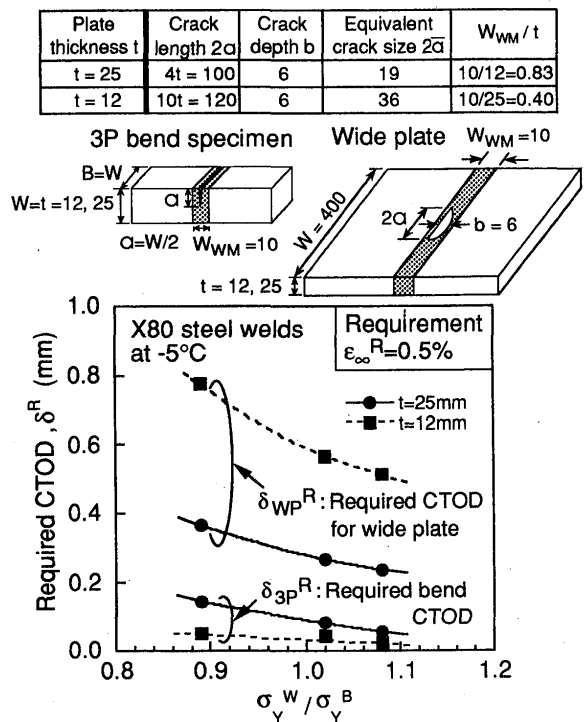


Fig. 27 Strength mis-match effect on required bend CTOD δ_{3P}^R and wide plate CTOD δ_{WP}^R for weld metal to meet design requirement ϵ_{∞}^R .

bend CTOD δ_{3P}^R , the equivalent CTOD, is much smaller than the required wide plate CTOD δ_{WP}^R .

The similar simulation was carried out to address the strain hardening effect of the material on the fracture toughness requirement. Undermatched weld metals with different strain hardenability were considered. Other bound-

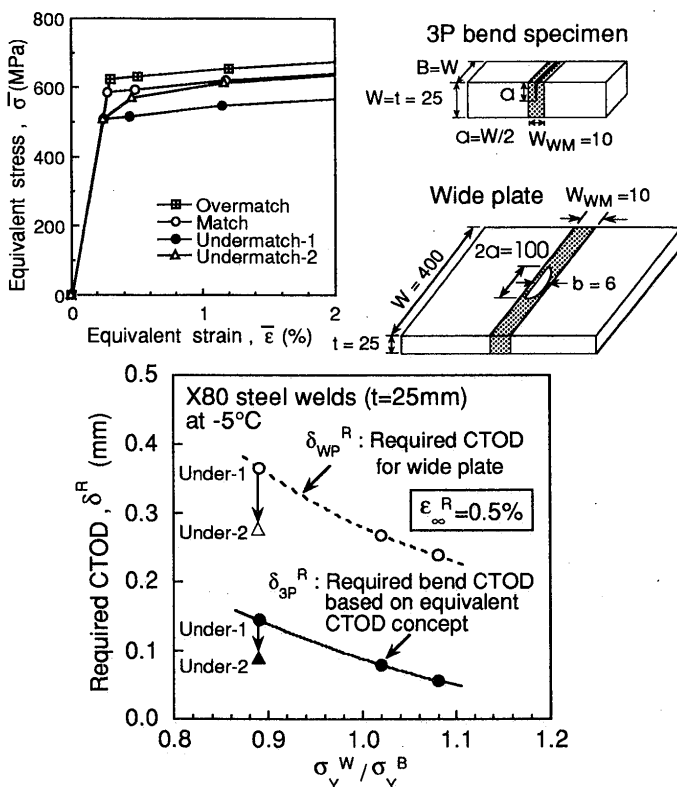


Fig. 28 Strain hardening effect on required bend CTOD δ_{3P}^R and wide plate CTOD δ_{WP}^R for weld metal to meet design requirement ϵ_{∞}^R .

ary conditions were not altered from the conditions used in Fig. 27. Figure 28 gives the result of the simulation. It is found that the required toughness in the undermatch situation could be compatible with that in the evenmatch situation, provided the undermatched weld metal exhibits a high hardening property.

7. Concluding Remarks

Fracture mechanics test results for welded joints are affected by the mechanical and metallurgical heterogeneity in welds. It was exhibited that the coarse-grained HAZ (CGHAZ) corresponds to the potential local brittle zone (LBZ) in welds which controls the initiation of brittle fracture. Larger sampling of the CGHAZ by the notch tip generally leads to a lower HAZ toughness. It was claimed that strength overmatching of the weld metal was not always beneficial, because the HAZ toughness was decreased with increasing the degree of strength overmatching of the weld metal. This is due to the constraint effect of the overmatched weld metal: The overmatched weld metal ele-

vates the local stress in the HAZ, which facilitates fracture initiation in the HAZ.

This paper employed the Local approach to quantify the cleavage resistance of heterogeneous welds. The key idea is the use of the Weibull stress, consisting of a local stress in a specific region responsible for fracture initiation, as a fracture driving force of welds. It was verified that the critical Weibull stress at fracture is independence of the strength mis-match condition near the notch tip. Besides the transferability of fracture toughness results to fracture performance evaluation of welded joints was confirmed by way of the Weibull stress analysis. These benefits of the Local approach led to a new procedure for fracture toughness requirement characterized by the equivalent CTOD concept. The new procedure quantifies the toughness requirement to meet a design solution of structural components as a function of strength mis-matching in welds.

Further applications of the Local approach are in progress; morphological investigation of microstructure to improve fracture resistance from viewpoint of stress/strain fields around local hard zones⁵⁴, small-size fracture toughness specimen utilizing constraint effect by strength mis-matching⁵⁵, and the evaluation of unstable fracture behavior under dynamic loading.

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