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Effect of Crack Depth and Strength Mis-Matching on the Relation between *J*-integral and CTOD for Welded Tensile Specimens†

Yukio UEDA*, Yaowu SHI**, Siying SUN** and Hidekazu MURAKAWA***

Abstract

In the present studies the effects of strength mis-matching of materials, crack length, and weld width on the relation between the J-integral and the crack tip opening displacement(CTOD) have been investigated using an elastic-plastic finite element method available in ABAQUS. The analysis is performed for a center-cracked welded specimens with strength mis-matching from M=0.8 to 1.2, crack length from a/W=0.1 to 0.5, and weld width from h/c=0.1 to 0.5. Effects of the strength mis-matching and the crack length on the plastic constraint factor are also discussed in detail.

The main results indicate that the strength mis-matching of materials has no influence on the relation between the J-integral and CTOD in elastic and small-scale yield regime. With increasing the load, effect of strength mis-matching appears to be notable. The plastic constraint factor investigated here may include the effect of the strength mis-matching on the local plastic deformation of welded joints. The crack length has a strong influence on the relation between the J-integral and CTOD as well as the constraint factor. Furthermore, the investigation indicates that the weld width appears to have no effect on the relation between the J-integral and CTOD, with the exception of very narrow weld widths.

KEY WORDS: (Fracture) (Welding) (Strength Mis-Match) (CTOD) (*J*-Integral) (Finite Element Method)

1. Introduction

It is well-known that welded joints are naturally inhomogeneous in microstructures and mechanical properties. In addition, fractures may often start from a relatively shallow cracks in welded joints or flame cutting edges only one or two millimeters deep. Thus, researchers have paid a great attention to investigate the effects of crack depth and strength mis-matching of materials on the crack driving force and crack growth resistance[1]. Common results indicate that the crack depth and strength mis-matching have an important influence on the elastic-plastic fracture of welded structures at temperatures above the initiation of ductile tearing.

As both the crack tip opening displacement(CTOD) and the *J*-integral are widely used as elastic-plastic fracture parameters in structural integrity assessment, many researchers have explored the relation between the two parameters in the elastic-plastic regime[2-4]. Usually this is relevant to the plastic constraint and the yield strength of materials in the homogeneous case. However, for cases involving material heterogeneity, studies of this topic have not been reported till now. At present there are no standard procedures for fracture mechanics testing of specimens with welds, because the heterogeneity of the welded joint makes the determination of the CTOD from the measurement of the crack mouth opening displacement(CMOD) more difficult. In addition, the accurate measurement of the CMOD is complicated when the crack depth becomes shallow. Therefore, it is attractive to use the *J*-integral instead of the CTOD.

In the present studies, the main aim is to investigate the effect of the strength mis-matching of materials and the crack depth on the relation between the values of the *J*-integral and CTOD. This research will give valuable information for carrying out the elastic-plastic fracture analysis of welded structures and establish a new standard procedure of fracture mechanics testing of welded specimens.

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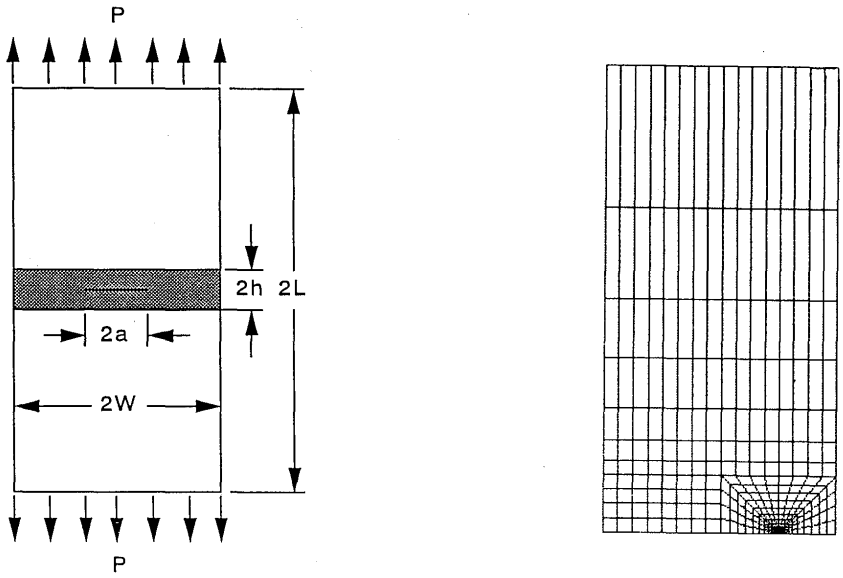


Fig.1 Configuration and FE mesh of center-cracked specimen.

2. Computational Model

In the present studies, an elastic-plastic finite element method(FEM) has been utilized to analyze the effects of the strength mis-matching of materials and crack depth on the *J*-integral and CTOD by using welded joint specimens as examples. Then, the relation of the two crack driving force parameters has been carefully discussed. As the tensile mode is dominant in the loading of most steel structures and the wide plate testing is commonly accepted as a realistic method to assess the fracture behaviour of welded structures, center-cracked tensile specimens are used in this numerical investigation, as shown in **Fig.1**.

In the computation, the base material is assumed to be the nuclear pressure vessel steel A508C13[5]. The properties of the steel are: yield strength σ_y=540MPa, ultimate tensile strength σ_{uts}=642MPa, elongation δ_5=22%, reduction φ=73%, and strain hardening coefficient n=6.5. It is assumed that the weldment consists of base metal and weld metal only, and the uniaxial tensile stress-strain relation follows the pure power hardening law which is given as,

$$\varepsilon/\varepsilon_y = \alpha(\sigma/\sigma_y)^n \quad (1)$$

In order to investigate the influence of the strength mismatching factor M, where M is the ratio of yield strength of weld metal to base metal in the range often met in practical situation, the values of M are chosen to be 0.8(undermatch), 1.0(evenmatch), and 1.2(overmatch). The strain hardening coefficient of the weld metal is assumed based on the following empirical equation[6],

$$n = 1/[k\ln(1390/\sigma_y)] \quad (2)$$

In the original equation k=0.12, but in this work the value of k is simply recalculated from the real properties of the A508C13 steel tested. The value of k becomes 0.163 in the present case. The values σ_y and n in Eq.(2) for the three types of matchings are presented in **Table 1**.

Considering that the vesssel diameter is far larger than the wall thickness, it is assumed that the computed specimen is in plane stress state.

Table 1 Materials matching of the computed welds.

	Base metal σ_y(MPa)	n	Weld metal σ_y(MPa)	n
Undermatched joint	540	6.50	432	5.26
Evenmatched joint	540	6.50	540	6.50
Overmatched joint	540	6.50	648	8.05

As this computation is mainly aimed at the effect of the strength mis-matching of weld metal and the crack depth on the crack driving force, as well as consideration of the combined effects with different weld widths simultaneously, three crack lengths and five weld widths are selected. Crack size parameter a/W is a ratio of half crack length to half specimen width, and weld width parameter h/c is a ratio of half weld width to half specimen ligament. In this computation, the values of a/W are chosen as 0.1, 0.25, and 0.5. The values of h/c are chosen as 0.1 to 0.5. The length and the width of the specimens are 2L=160mm, and 2W=80mm, respectively.

The present elastic-plastic FEM computations are performed using ABAQUS[7]. Due to the symmetry, only one-quarter of the model is analyzed. An eight-node isoparametric element is used, and singularity at the crack tip is modelled by deforming the elements at the tip to triangles with one edge of the element shrunk into one point. The meshes have a total of 316 elements and 1037 nodes. All the computation is conducted on an Alpha Station 600.

In the computation, the values of J-integral are evaluated by six contours. The CTOD value is taken as the crack opening displacement at the position 0.1mm behind the crack tip[8].

In the present computation, the specimens are loaded by distributed uniform tension, and the maximum load applied is $P = 1.4P_0$ where P_0 is the limit load. Under plane stress condition, it is given by,

$$P_0 = 2\sigma_0(W-a) \tag{3}$$

where σ_0 is the yield stress of the material.

3. Results and Discussions

3.1 Effect of strength mis-matching

Based on a series of computations, the relations between the J-integral and CTOD are shown in **Fig.2** for the specimens with different crack lengths. With the increase of the load, the values of J-integral are increased with the CTOD simultaneously. However, the increasing rate of the J-integral gradually becomes larger with the increase of the CTOD. In the conditions where the specimens have the same crack length, it is clear that the curves in the elastic and small-scale yield regime are almost overlapping for the even- or mis-matched joints. With further increase of the load, the curves tend to separate from each other. Among them, the increasing rate of the J-integral for the undermatched joints is the fastest, and those for the overmatched joints is the slowest. This is especially clear for the specimens with a/W=0.25, as shown in Fig.2(b), where the applied crack driving force is larger than the other specimens. It is also seen that the characteristic is almost the same for the specimens with different crack lengths.

For homogeneous materials with small-scale yielding, several theoretical and numerical studies have suggested that there exists a relation between the J-integral and CTOD as follows[3]:

$$J = m\sigma_y\delta \tag{4}$$

where δ is the CTOD value, and m is the plastic constraint factor, which is related to both the plastic constraint and the strain hardening of the materials. For the plane stress state m=1, and for the plane strain state $1<m<3$. For the conditions of large-scale or full yielding, however, the effect on m is much complicated.

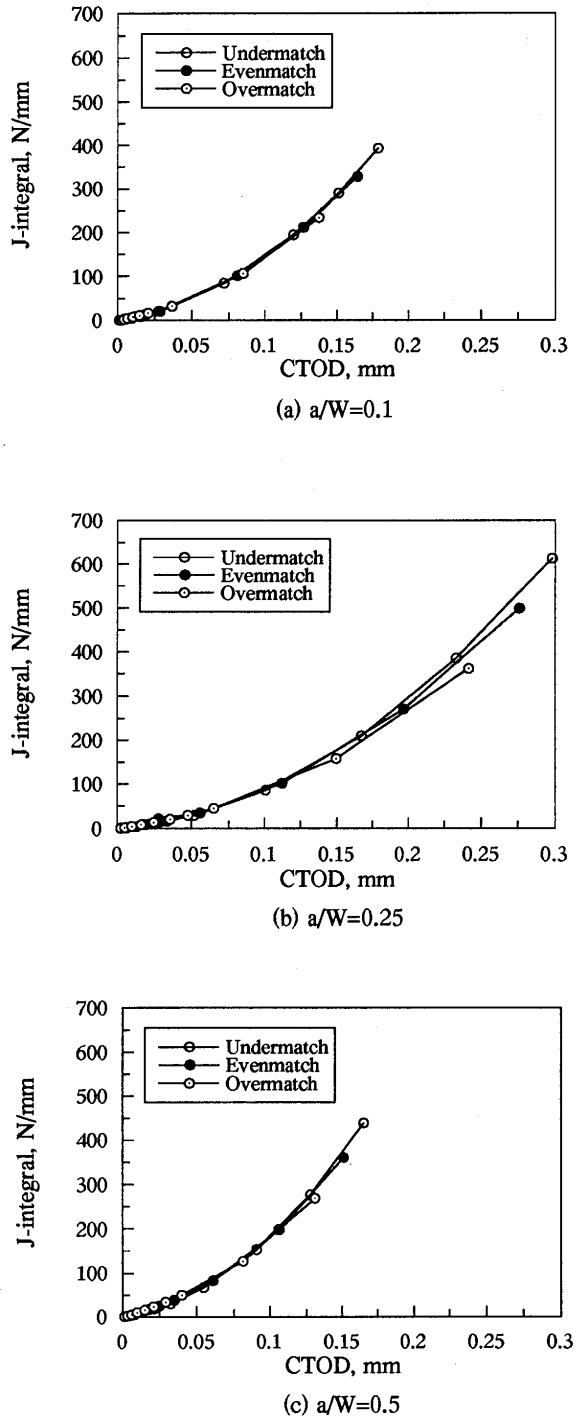
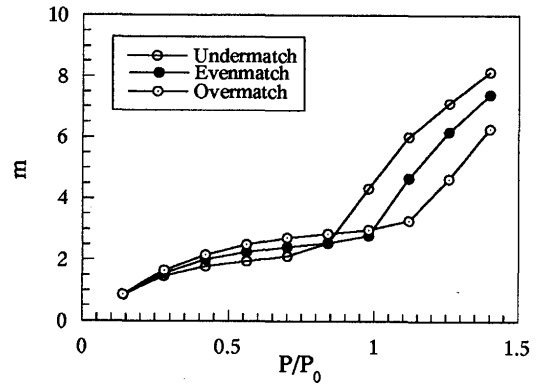
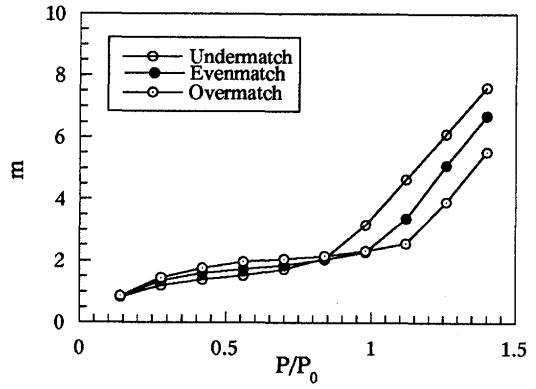


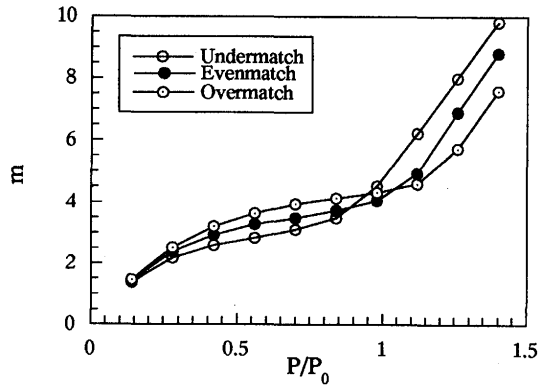
Fig.2 Effect of weld strength mismatch on the relation between J-integral and CTOD(h/c=0.4).



(a) a/W=0.1



(b) a/W=0.25



(c) a/W=0.5

Fig.3 Effect of weld strength mis-matching on the plastic constraint factor.

Based on Eq.(4), Fig.2 can be replotted as **Fig.3**, in which σ_y is the yield strength of the base material. It is indicated from Fig.3 that the values of m increase with increasing normalized load P/P_0. The rate of increase observed in m is relatively small when the normalized load P/P_0 is smaller than one, but it clearly becomes large when P/P_0 is great than one. The increasing rate of m with the loading may be related to the change from small-scale to large-scale or full yielding.

Effects of the strength mis-matching on the plastic constraint factor m are much more clearly shown in Fig.3. When the P/P_0 is larger than one, the values of m for undermatched joints are the highest, and those of overmatched joints are the lowest among the different mis-matched welded joints. However, when the load P/P_0 is smaller than one, the situation is reversed, that is, the values of m for overmatched joints are higher than those for evenmatched joints, and the values of m for undermatched joints are lower than those for evenmatched joints. Generally speaking, when the load P/P_0 is smaller than one, the effect of the strength mis-matching on the m values is weak. However, when the load P/P_0 is larger than one, the effect of the strength mis-matching becomes significant. Moreover, the effects of the strength mis-matching on the m values are almost the same for the specimens with different crack lengths.

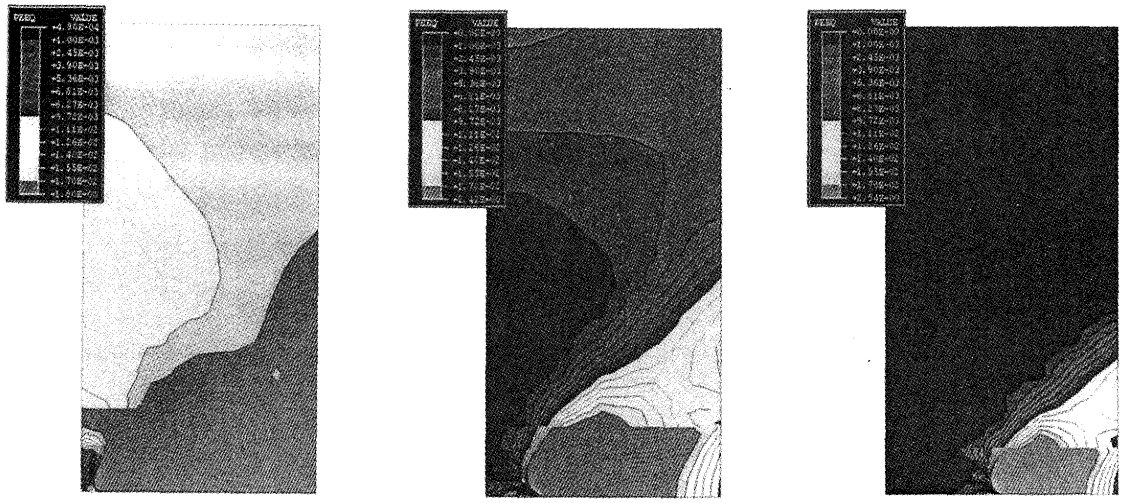
It has been proposed for homogeneous materials that the factor m may have a form which is different from the relation in Eq.(4). In this expression, the factor m may be determined from the following equation[2],

$$m = \frac{1}{0.55(1+n)} \frac{2}{\sqrt{3}} [(1+\nu)(1+n)\frac{\sigma_y}{nE}]^{-n} \qquad (5)$$

where n is the strain hardening exponent under the form of σ-$(\varepsilon_p)^n$. Although the basis of the above expression is small-scale yielding and a plane strain state, it is clear that the factor m is dependent on σ_y/E, n and stress state. In the previous studies on the equivalent parameters, it is indicated that the material parameters such as yield stress and strain hardening exponent ahead of the crack tip are strongly influenced by the mis-matching of welded joints[9-11]. Thus, it is inferred that the m values obtained from this calculation may include the effect of the strength mis-matching on the local plastic deformation of welded joints, because only the yield strength of the base material is used in the calculation of m.

3.2 Effect of crack length

In the elastic-plastic regime for deep crack specimens, plastic flow is confined to the ligament of the specimen and a high hydrostatic component of stress is maintained at the tip. However, for the shallow crack specimens the plastic flow spreads to the free surface behind the crack tip and the yielding reaching the free surface causes a loss of crack tip constraint. In this case, the short crack specimen must undergo larger crack tip blunting and



(a) a/W=0.1 (b) a/W=0.25 (c) a/W=0.5

Fig.4 Effect of crack length on the equivalent plastic strain for the weld strength undermatched specimens loaded at P=1.4P_0 (h/c=0.4).

plastic deformation than deep crack specimens to develop the same critical stress and strain at the crack tip required to cause the onset of crack growth. Thus, crack length, which influences the plastic constraint of crack tip, must be an important parameter in the relation between J-integral and CTOD.

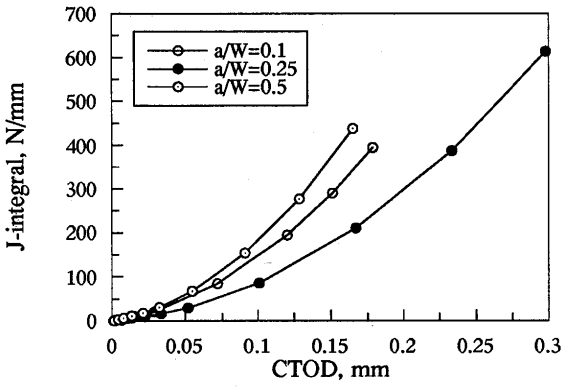
Figure 4 shows the effect of the crack length on the yielding ahead of the crack tip for the undermatched joints. All the specimens with the same h/c values of 0.4 are loaded to P=1.4P_0 It is clear that the yield region is rapidly expanding with the decrease of the crack length, and the heavy yield region is expanding to the back of the crack tip when the weld metal is undermatched, as shown in Fig.4(a). This results are quite similar to the previous investigation on the three-point bend specimens[12].

The effects of the crack length on the relation between J-integral and CTOD are summarized in **Fig.5**. Recently, some results show that the crack length appears to have very little effect on the constraint factor[13]. However, in this study, it is indicated that crack lengths have a strong influence on the relation between J-integral and CTOD. The increasing rate of the J-integral with the increasing of the CTOD is the highest for the specimens with a/W=0.5 and the lowest for the specimens with a/W=0.25. Such tendency is the same for the specimens with different mis-matching.

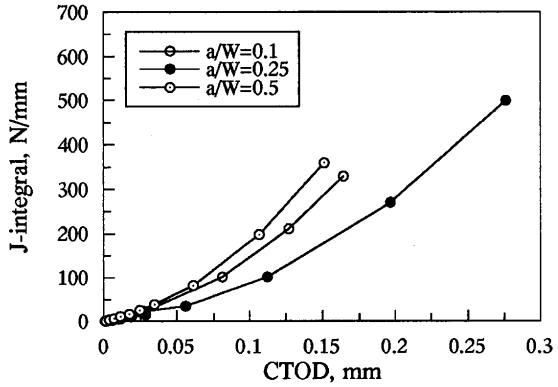
Figure 6 is replotted from Fig.5, in which the factor m is calculated from Eq.(4). Like Fig.3, the values of m are increased with the increase of the normalized load P/P_0. The increasing rate of m is lower before about one, but it clearly becomes higher when load P/P_0 is roughly greater than one. This tendency is the same for the specimens with different mis-matching of welds. However, effects of the crack length on the plastic constraint factor m are different. In the whole loading range investigated, the value of m for the specimens with a/W=0.5 are all higher than the other specimens. This is because the deep or long crack specimens have more severe constraint at the crack tip. On the contrary, m for the specimens with a/W=0.25 are all lower than the others. The fact that the m values for the specimens with a/W=0.25 are even lower than those for the specimens with a/W=0.1 may be explained by the reported test results[14-17]. In a series of three-point bending tests previously conducted on ductile steels, it was indicated that there exists a peak in the curve of J-integral at the onset of crack growth for the specimens with crack lengths from a/W=0.05 to 0.5.

3.3 Effect of weld width

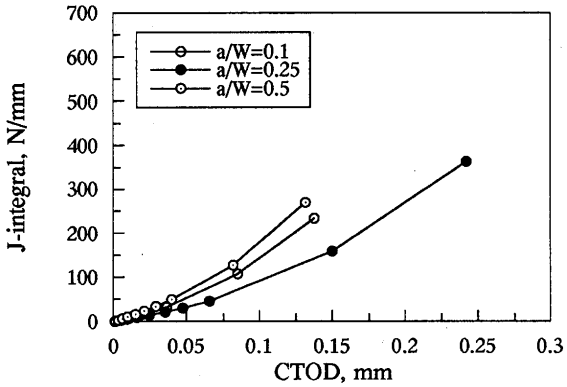
the previous studies, it was indicated that the weld width may have an significant influence on the crack driving force[9]. Thus, the effect of the weld width on the



(a) Undermatched joint

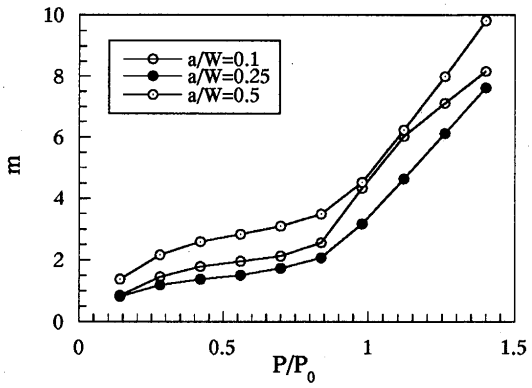


(b) Evenmatched joint

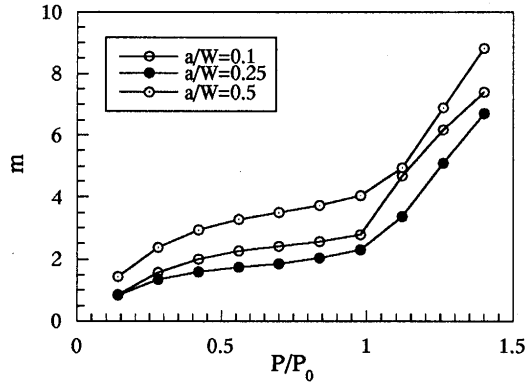


(c) Overmatched joint

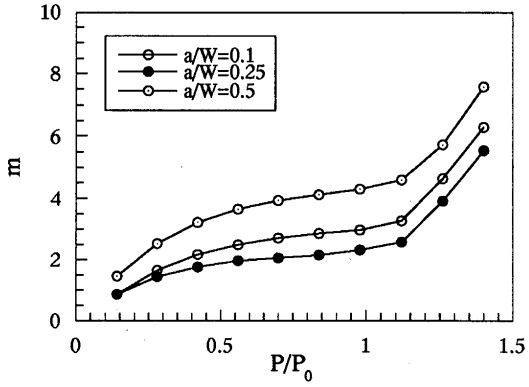
Fig.5 Effect of crack length on the relation between J-integral and CTOD(h/c=0.4)



(a) Undermatched joint



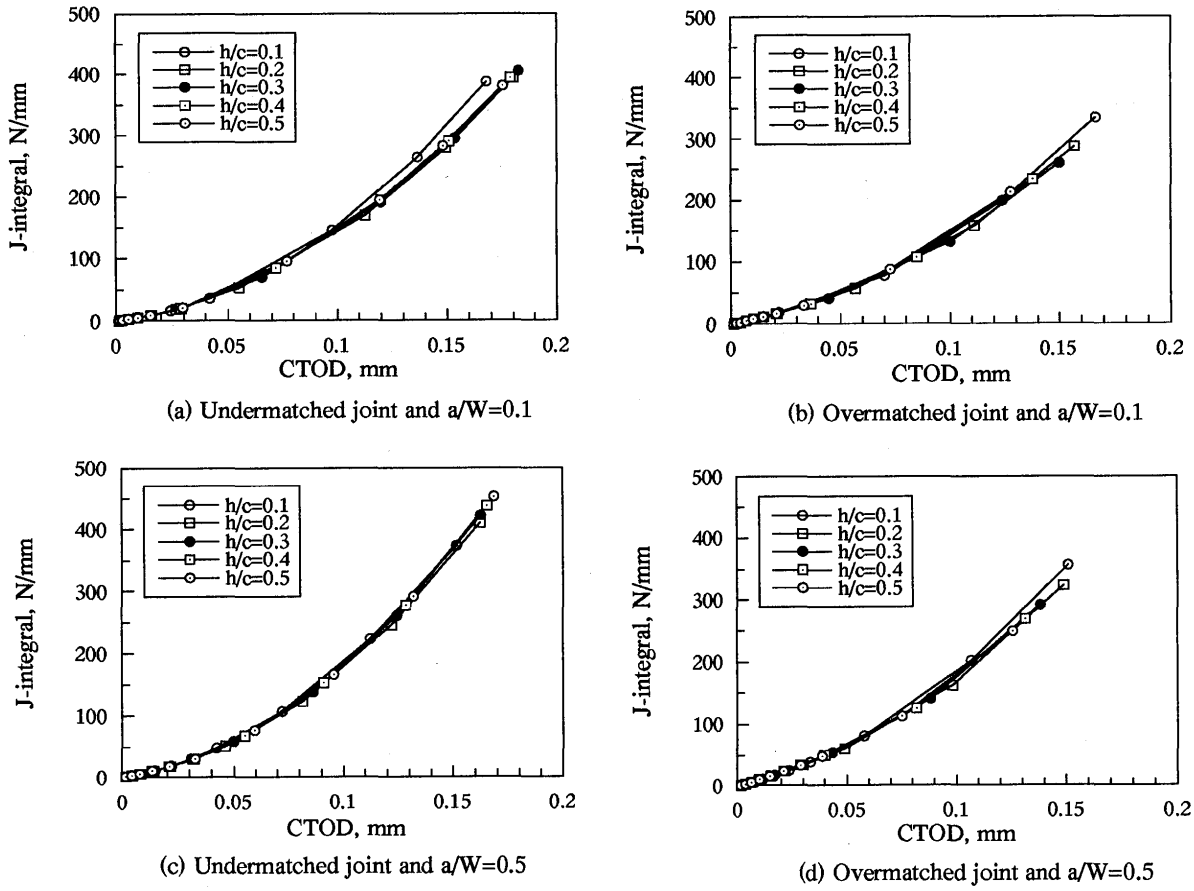
(b) Evenmatched joint



(c) Overmatched joint

Fig.6 Effect of crack length on the plastic constraint factor

relation between J-integral and CTOD has been investigated in the present study and the results are shown in Fig.7. It is clear that weld width appears to have almost no effect on the relation between J-integral and CTOD in the investigated range from a/W=0.1 to 0.5. Moreover, there exists almost the same tendency for the



(a) Undermatched joint and a/W=0.1

(b) Overmatched joint and a/W=0.1

(c) Undermatched joint and a/W=0.5

(d) Overmatched joint and a/W=0.5

Fig.7 Effect of weld width on the relation between *J*-integral and CTOD.

specimens with different weld strength mismatching and different crack lengths. Only cases where specimens with a/W=0.1 may be somewhat exceptional. Thus, the effect of the weld width on the relation between *J*-integral and CTOD may be neglected, with the exception of those cases with very narrow weld widths.

4. Conclusions

(1) In the elastic and small-scale yield regime, strength mis-matching has no influence on the relation between *J*-integral and CTOD. With increasing the load, the effect of weld strength mis-matching occurs. When the plastic constraint factor is plotted against the normalized load, the effect of the weld strength mis-matching appears to be notable. It is felt that the constraint factor obtained may include the effect of the strength mis-matching on the local plastic deformation of welded joints.

(2) For the center-cracked tensile specimens, the effect of the crack length on yielding at the crack tip is the same as that for three-point bend specimens. The crack length, or the depth, has an important influence on the relation between *J*-integral and CTOD as well as the constraint factor.

(3) The weld width appears to have almost no effect on the relation between *J*-integral and CTOD, with the exception of very narrow weld widths.

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References

1) F.M.Burdekin, M.Kocak, K.H.Schwalbe, and R.Denys, Significance of strength mis-match in welds - summary of a round table discussion, *Mis-Matching of Welds*, ESIS 17, Ed. K.H.Schwalbe and M.Kocak, Mechanical Engineering Publications, London, 1994, pp.103-111.

2) R.M.McMeeking, Finite deformation analysis of crack-tip opening in elastic-plastic materials and implications for fracture, *Journal of Mechanics and Physics of Solids*, Vol.25, 1977, pp.357-381.

3) M.G.Dawes, Elastic-plastic fracture toughness based on the CTOD and *J*-contour integral concepts, *Elastic-*

Plastic Fracture, ASTM STP668, Ed.J.D.Landes et al., ASTM, 1979, pp.307-333.

4) Y.W.Shi, and Z.X.Han, The effects of crack depth on the *J*-integral and CTOD fracture toughness for welded bend specimens, *Fatigue and Fracture of Engineering Materials and Structures*, Vol.16, 1993, pp.281-287.
5) Y.W.Shi, J.X.Zhang, and X.P.Zhang, An elastic-plastic fracture analysis approach and radiation embrittlement monitoring technique by means of small samples for nuclear pressure vessel, *Final Report for appraisal, No.75-19-03-05, Xi'an Jiao-tong University*, Xi'an, 1990.
6) H.Yoshinari, On the methods for fracture strength assessment, Journal of the *Japan Welding Society*, Vol.64, 1995, pp.422-431.
7) ABAQUS/Standard User's Manual, Version 5.5, Hibbitt, Karlsson & Sorensen, Inc. logo, USA, 1995.
8) S.Machida, Y.Hagiwara, T.Inoue, S.Aihara, and K.Itoh, Significance of HAZ toughness in offshore structures based on fracture mechanics, *Proceedings of the Eighth International Conference on Offshore Mechanics and Arctic Engineering*, Vol.3, Ed. M.M.Salama et al., ASME, 1989, pp.691-698.
9) J.X.Zhang, Y.W.Shi, and M.J.Tu, Studies on the fracture mechanics parameters of weldment with mechanical heterogeneity, *Engineering Fracture Mechanics*, Vol.34, 1989, pp.1041-1050.
10) J.X.Zhang, Y.W.Shi, and M.J.Tu, Factors affecting the estimation of fracture mechanics parameters of center-cracked weldment, *Engineering Fracture Mechanics*, Vol.50, 1995, pp.537-543.
11) Y.W.Shi, Z.X.Han, and N.N.Zhou, Estimates of local tensile strength of welded joints, *International Journal of Pressure Vessel and Piping*, Vol.65, 1996, pp.41-45.
12) W.Tang, and Y.W.Shi, Influence of crack depth and strength matching on deformation and plastic zone for welded joint specimen, *International Journal of Fracture*, Vol.74, 1995, pp.77-87.
13) W.A.Sorem, R.H.Dodds Jr, and S.T.Rolfe, A comparison of the *J*-integral and CTOD parameters for short crack specimen testing, *Welding Research Council Bulletin*, No.351, February, 1990, pp.24-34.
14) J.Xie and Y.W.Shi, Fracture toughness for the specimens with shallow cracks, *Engineering Fracture Mechanics*, Vol.32, 1989, pp.329-337.
15) J.Xie and Y.W.Shi, Effect of yield stress and specimen size on the position of fracture toughness peak(FTP) in J_i-a/W curves, *Engineering Fracture Mechanics*, Vol.33, 1989, pp.907-912.
16) W.Tang, and Y.W.Shi, Influence of strength matching and crack depth on fracture toughness of welded joints, *Engineering Fracture Mechanics*, Vol.51, 1995, pp.649-659.
17) Y.W.Shi, Z.X.Han, N.N.Zhou, and J.Li, The significance of crack depth in fracture toughness specimens for HSLA steel welds, *Engineering Fracture Mechanics*, Vol. 41, 1992, pp.143-151.