Abstract

Bimaterial CT specimens are numerically analyzed in the elastic-plastic states. By changing the material constants and the distance between the crack tip and the phase boundary, the parametric analyses are conducted. J integral evaluated by the line integration is compared with that obtained by the empirical formula by Merkle-Corteni. The effects of the inhomogeneities on the accuracy of the J integral evaluation are discussed. Next the stable crack growth analyses are conducted. Using the relation between $\delta a$ and load-load line displacement obtained experimentally, the generation phase analyses are carried out. J integral, $T^*$ integral and $CTOA$ are evaluated and the effects of the fusion line are discussed.

1 Introduction

In the fracture mechanics of homogeneous materials, the availability of the J integral concept is well known. But in the inhomogeneous material, we should consider two problems for the use of the J integral concept. One is the availability of the empirical formulas to evaluate the
J integral, which is widely used in the fracture toughness testing of homogeneous material. Another is the problem of the path independency of the J integral to evaluate it numerically.

In the EPI research project (Elastic-Plastic fracture mechanics of Inhomogeneous material, Chairman: Prof. G. Yagawa of University of Tokyo) between Japanese and US consortia, two kinds of benchmark analyses are conducted. The first one is the analyses of stationary cracks, and another one is the analyses of stable crack growth problem. In both cases, the crack exists in the welded CT specimen, and the initial crack is located vertical to the fusion line. By changing the location of the crack tip and the material constants, the effect of the inhomogeneities on the J integral and other fracture mechanics parameters are studied. The final goal of this study is to establish a new conventional scheme to estimate the fracture parameter of inhomogeneous CT specimen.

2 Stationary Crack Problem

2.1 Benchmark Problem.

A bimaterial CT specimen as shown in Fig.1 is analyzed. Its size and configuration are determined based on a standardized 1CT specimen. The crack is set to be vertical to the specimen's phase boundary. The initial crack tip is placed beside the phase boundary. This kind of arrangement of two materials and a crack often found in the test of welded CT specimens. That is, the materials #1 and #2 in Fig.1 may correspond to base metal and weld metal, respectively.

The material properties of two metals are taken from the experiments on the base metal of welded plate made of A533 class 1 steel[1]. The uniaxial stress-strain relation of base metal is as follows:

\[
\sigma \leq \sigma_{YS} \quad \varepsilon = \frac{\sigma}{E} \quad (1)
\]

\[
\sigma \geq \sigma_{YS} \quad \varepsilon^p \leq 0.02153 \quad \varepsilon = \frac{\sigma}{E} + \left\{ \left( \frac{\sigma}{E'} \right)^n - \left( \frac{\sigma_{YS}}{E'} \right)^n \right\}
\]

\[
\varepsilon^p \geq 0.02153 \quad \varepsilon = \frac{\sigma}{E} + \left\{ \left( \frac{\sigma}{E''} \right)^{n'} - \left( \frac{\sigma_{YS}}{E''} \right)^{n'} \right\} + \varepsilon_0
\]

where E is 206 GPa, \(\nu=0.3\), \(\sigma_{YS}=550\) MPa, \(n=2\), \(E'=500\) MPa, \(E''=850\) MPa, \(n'=10\), \(\sigma_{YS}'=554.9\) MPa, and \(\varepsilon_0=0.02153\).

For the weld metal, the following relation is used:

\[
\sigma \leq \sigma_{YS} \quad \varepsilon = \frac{\sigma}{E} \quad (2)
\]

\[
\sigma \geq \sigma_{YS} \quad \varepsilon = \frac{\sigma}{E'} + \left\{ \left( \frac{\sigma}{E'} \right)^n - \left( \frac{\sigma_{YS}}{E'} \right)^n \right\}
\]

where \(\sigma_{YS}=630\) MPa, \(E'=950\) MPa and \(n=8\). Young's modulus and yield stress of weld metal are changed in several cases.

In the parametric study, three parameters are varied. They are:
(1) The distance between the crack tip and the phase boundary.
(2) The ratio of Young's modulus of two materials.
(3) The ratio of the yield stress of two materials.

As shown in Table 1, 13 cases are assumed by changing these parameters. The analyses are performed considering the following issues:
(a) Each participant chooses an appropriate mesh by themselves.
(b) J integral is calculated along the near-tip path set in the material #1.
(c) J integral is calculated by Merkle-Corten’s formula using load-load line displacement curve.
(d) Path distribution of J integral is examined.

Four members participated the analysis. All the members used the 8-noded isoparametric element in FEM code, but the number of elements and nodes they used are varied. In the finest case, more than 2000 nodes are used, and in the coarsest case, the number of nodes is about 300. Three members used the line integral method in the evaluation of the J integral, and the one used the virtual crack extension method.

2.2 Results and discussions.

In the following, J integral calculated by the line integration or the virtual crack extension method is called \( J_p \), and \( J_{M-C} \) is the J integral obtained by the empirical formula by Merkle and Corten. Fig.2 shows the comparison of Cases 1, 5 and 8, which show the effect of the yield stress. In the homogeneous material, Case 1, \( J_p \) and \( J_{M-C} \) coincides well. In Case 5, though they are similar to each other, \( J_{M-C} \) is slightly larger than \( J_p \). And in Case 8, where the difference of the yield stress between the base metal and the weld metal is the largest, \( J_{M-C} \) is much larger than \( J_p \). In the final stage of the deformation, \( J_{M-C} \) is nearly 10 larger than \( J_p \) value. These results mean that the increase of the yield stress of the weld metal promotes the overestimate of the \( J_{M-C} \) value.

Fig.3 shows the effect of the Young's modulus. In Case 2, where the Young's modulus of the weld metal is 15% larger than that of the base metal, \( J_{M-C} \) is larger than \( J_p \). In Case 3, where the difference of the Young’s modulus is 45%. \( J_{M-C} \) and \( J_p \) values become similar to each other. In these two cases, the ratio of the yield stress is the largest. Then the reason that the \( J_{M-C} \) is larger than \( J_p \) is due to the difference of the yield stress. The increase of the difference of the Young’s modulus, which corresponds to the decrease of the ratio of the Young's modulus, causes the decrease of the \( J_{M-C} \) value.

Fig.4 shows the results where the differences of the Young's modulus and the yield stress between the two metals are the smallest. In Case 4, where the distance is the smallest, \( J_{M-C} \) is a little larger than \( J_p \). But as the distance increases, in Cases 6 and 13, both the values agrees well. It means that the differences of the material properties in these cases have little effect on the evaluation of the J integral, except when the crack tip is located very near the phase boundary.

Fig.5 shows the results where the differences of the material properties are the largest. In Case 3, the distance is the smallest, \( J_{M-C} \) is smaller than \( J_p \) for the small displacement. This is due to the effect of the difference of the Young's modulus, because the elastic deformation is dominant in the beginning of the deformation. As the deformation increases, the effect of the plastic deformation, therefore the effect of the difference of the yield stress becomes dominant, and \( J_{M-C} \) becomes larger than \( J_p \) where the displacement is 0.64mm. In Case
10, both values show similar results, but the difference between the two values are larger than those in Case 3, and they cross after large deformation, such as when the displacement is 1.4 mm. In Case 12, where the distance is the largest, \( J_{M-C} \) is smaller than \( J_p \) to the final stage of the deformation.

Whether \( J_{M-C} \) overestimates the \( J \) value or underestimates it is not concluded easily. It depends on the combination of the material properties and the distance between the crack tip and the phase boundary. However as shown in these figures, the differences of the \( J_{M-C} \) and \( J_p \) values are below 10 to 20%. In the fracture toughness testing standards[3,4], the experimental error below 25% is permitted. The differences shown in the numerical analyses are smaller than the error limit of the experiment. It can be concluded that the differences of the present material properties assumed in this parametric study don’t cause any difficulty in the experimental evaluation of the \( J \) integral values, and \( J \) value is estimated within an adequate accuracy by the use of the empirical formula.

In Fig.6, the \( J \) values of each integration path in several cases are shown. In Cases 2 and 12, the broken line denotes the position of the phase boundary, paths on the right of this line are to cross the phase boundary. In Case 8, all paths cross the phase boundary. In Cases 2 and 8, the effect of the phase boundary on the evaluations of the \( J \) integral are negligible, and show good path independency. In Case 12, the effect of the phase boundary is clearly recognized. Case 12 uses the virtual crack extension method. In the homogeneous material, both the line integral method and the virtual crack extension method give similar \( J \) values. But in the inhomogeneous problem, the effect of the evaluation method on the \( J \) value has not been studied much. It may be a problem dealt with in the future EPJ program.

3 Growing Crack Problems

3.1 Benchmark Problem

Analyzed here are one homogeneous and three welded CT specimens with different crack tip locations as shown in Fig.1. 20% side groove is machined in all the specimens. They are:

1. M5G specimen, which is a homogeneous CT specimen made of the base metal.
2. H5G specimen, in which a crack tip is located in front of the phase boundary, i.e. in HAZ.
3. F5G specimen, in which a crack tip is located on the phase boundary.
4. D5G specimen, in which a crack is located across the phase boundary.

The stress-strain relations used in the present analyses are basically the same as those of eqs.(1) and (2). Young’s moduli of the material #1 and #2 are taken to be 206 GPa and 175 GPa, respectively, while their yield stresses are 550 MPa and 630 MPa, respectively. Generation phase crack growth analyses are carried out following the measured relationships among a load per unit thickness (P), a load-line displacement (\( \delta a \)) and a crack extension amount (\( \Delta a \)). Nine participants performed the present analyses. All the participants use eight-noded isoparametric elements. The finest mesh consists of about 1300 nodes, while the coarsest mesh does about 500 nodes. Eight participants use the line integration technique for the \( J \) integral calculation, while the rest one use the virtual crack extension method. All the
participants use a nodal release technique to simulate stable crack growth. The following fracture mechanics parameters are plotted against $\Delta a$: the $J$ integral calculated along the integration paths, $J_{path}$, the $J$ integral evaluated by the Merkle-Corten's formula, $J_{M-G}$, the modified $J$ integral by Ernst[5], $J_M$, the deformed $J$ integral by Ernst et al.[6], $J_D$, the $T^*$ integral[7], the $\tilde{J}$ integral[8] and CTOA. It is well known that the conventional $J$ integral calculated along the integration paths loses any physical meaning and a path independency when large scale crack growth occurs. Nonetheless, we calculate $J_{path}$ values along various integration paths because one of purposes of the present analyses is to study the correlation of $J_{path}$ with $J_{M-G}$, $J_M$ and $J_D$ during crack growth in inhomogeneous materials.

3.2 Results and Discussions

Fig.7 shows the calculated and measured crack growth resistance curves of M5G specimens, where solid circles indicates the measured $J_D$ and others calculated values, i.e. $J_D$ (open circles), $J_M$(open squares), $J_{M-G}$(open triangles). $J_{path}$ calculated along the farthest path(dashed line), and $T^*$ (solid line). The following observations can be derived from the figure.

1. Calculated and measured $J_D$ values agree well with each other within $10\%$ difference.
2. All the $J$ values increase continuously in accordance with crack growth, while the $T^*$ value levels off after a certain amount of crack growth. The $J$ integral showed the similar trend to the $T^*$ integral although it is not shown in this particular case.
3. The order of magnitudes of the $J$ values is as follows; $J_M > J_{M-G} > J_D$. It should be noted that $J_{path}$ values have shown strong path dependency.

Fig.8 shows the crack growth resistance curves of H5G specimen. The following observations can be obtained from the comparison of both figures.

4. Crack growth resistance of M5G is greater than that of H5G, even if evaluating by $J$ integrals.
5. The slopes of $J-R$ curves of H5G are steeper than those of M5G.
6. The $T^*$ integral always levels off after a certain amount of crack growth, and the magnitude of the $T^*$ of M5G is greater than that of H5G. In H5G specimen, the $T^*$ increases gradually after crossing the phase boundary.

Those results may be attributed due to the fact that the HAZ part has lower initiation toughness than both weld and base metals.

Figs.9 and 10 show the crack tip strain and stress distributions of M5G and H5G specimens along uncracked ligaments, i.e. $\theta = 0^\circ$ at crack initiation. The crack tip strain field is continuous at the phase boundary, while the stress field shows jump of about 15%, which almost corresponds to the difference of yield stresses of both materials. For the purpose of comparison, the theoretical HRR fields[9,10] using yield stresses of both materials are plotted here. It can be expected that the HRR fields in a homogeneous material regime may be adjustable to a stationary crack in a bimaterial regime. However, the analyses on crack tip fields during crack growth in homogeneous and bimaterial specimens also show that the HRR slope disappears after a certain amount of crack growth.
4 Concluding remarks.

Elastic-plastic finite element analyses are carried out on stationary and growing cracks in welded CT specimens, whose material properties and crack growth histories are obtained experimentally. The analytical results clearly show the quantitative effects of material inhomogeneities on fracture mechanics parameters.

It is clearly demonstrated that the parametric numerical analysis is very effective for the study of complicated phenomena such as the EPI problem, in which the number of parameters is greater compared with the homogeneous problem. It is concluded that the parametric numerical study may be a key procedure in the EPI program. In this study, the analyses are restricted to only the two-dimensional crack problems. Three dimensional analyses will be carried out in the future EPI program.

Acknowledgement

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References
(1) EPI Subcommittee Report (II), JWES-AE-9004, May 1990
(2) J.G. Merkle and H.T. Corten, Trans. ASME, 1974, p.286
(4) JSME Standards (in Japanese), JSME S001,1981
(10) J.R.Rice et al., ibid, 18(1968), p.1
Table 1 Conditions for bi-material CT specimen analysis.

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Fig. 1 Bi-material CT specimen.

Fig. 2 Comparison of $J_{M-C}$ and $J_p$. (Effect of yield stress.)
**Case 2**

Fig.3 Comparison of $J_{M-C}$ and $J_p$. (Effect of Young's modulus.)

**Case 3**

**Case 4**

**Case 6**

**Case 13**

Fig.4 Comparison of $J_{M-C}$ and $J_p$. (Effect of $c/b$.)
Fig. 5 Comparison of $J_{M-C}$ and $J_p$ (Effect of $c/b$.)

Fig. 6 $J$ values for each integration path.
Fig. 7 Measured and calculated crack growth resistance curves of M5G specimen.

Fig. 8 Measured and calculated crack growth resistance curves of H5G specimen.

Fig. 9 Comparison of crack-tip strain fields of M5G and H5G specimens.
Fig. 10 Comparison of crack-tip stress fields of M5G and H5G specimens.