Elastoplastic Fracture Parameters for a Joint Containing a Transverse Crack in the Longitudinal Overmatched Weld*

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ABSTRACT

A welded joint with a transverse crack in a hard weld or HAZ is simplified as a model of the strip with a longitudinal sandwiched hard layer containing a crack perpendicular to interfaces. The *J*-integral, COD at the centre of the crack and load-point-displacement in models containing a hard layer of different width are calculated by means of the elastoplastic FEM under plane stress condition. The effects of mechanical heterogeneity are described by a comparison of the results obtained by the FEM with those estimated by the EPRI engineering approach for homogeneous material. The results of our study showed that in the nonlinear stage, the effects of heterogeneity are similar to those in the models with a transverse sandwiched hard layer containing a crack parallel to the interfaces. The ratios of the values computed by the FEM for heterogeneous models to those by the EPRI approach can be regarded as modifying coefficients.

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KEYWORDS

Fracture; welded joint; *J*-integral; COD; heterogeneity.

INTRODUCTION

It is well known that the fracture of welded structures is generally caused by various defects in welded joints, while macro-mechanical heterogeneity is one of their major features. As the service temperature of some welded structures is higher than the ductile-brittle transition temperature, a large yield region is produced usually before fracture occurs. In this case, linear elastic fracture mechanics is no longer applicable, and only elastoplastic fracture mechanics should be used. Therefore, the research of elastoplastic fracture parameters for heterogeneous welded joints is of theoretical significance.

The EPRI approach (Kumar, *et al.*, 1981) has made it convenient to apply elastoplastic fracture mechanics to engineering. But it is only a method applicable to homogeneous materials, and it is also questionable to be applied in analysing the safety of welded joints which are heterogeneous to some extent.

Heterogeneous welded joints can be simplified to be sandwiched models with a crack in different regions and in different directions (Radaj, 1976). Ma *et al.* (1986) reported the research results of the elastoplastic fracture parameters in a model as shown in Fig.1(a) which contains a crack parallel to the bi-material interfaces.

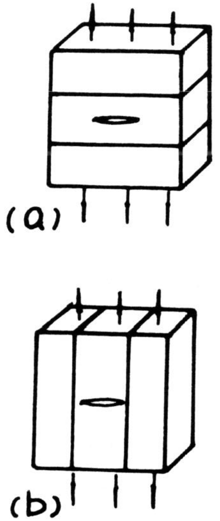


Fig.1. Simplified model of welded joints containing a crack. (a) Parallel crack; (b) Perpendicular crack.

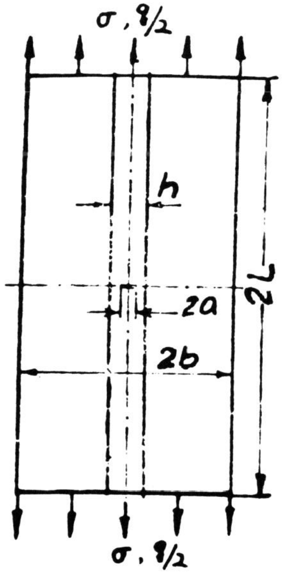


Fig.2. Model used for FEM analysis.

In order to get a full view of the effect of heterogeneity of welded joints on fracture parameters, it is necessary to investigate another typical model as shown in Fig.1(b), which contains a crack perpendicular to the interfaces.

PROCEDURE OF THE ANALYSIS

A simplified model of an overmatched welded joint is shown in Fig.2, which is in tension on the ends and which contains a transverse crack in a weld or HAZ, namely a crack perpendicular to the longitudinal direction in the hard layer. The length of the model is 2L=160mm, the width 2b=64mm, the length of the crack 2a=8mm, the ratios of the hard layer width to the crack length h/2a=0.00, 1.00, 1.25, 1.50, 2.00, 3.00, and ∞, respectively.

The nominal yield stresses of the hard layer and the base material (soft zone) are σ_{yh}=1332 MPa and σ_{ys}=666 MPa, respectively. The Young's modulus E=2.0×10⁵ MPa and Poisson's ratio ν=0.3 for both materials. Their stress-strain relations obey the Ramberg-Osgood law:

$$\frac{\epsilon}{0.666\times 10^{-2}} = \frac{\sigma}{1332} + 0.30\times\left(\frac{\sigma}{1332}\right)^{5} \quad \text{(the hard layer material)}$$

$$\frac{\epsilon}{0.332\times 10^{-2}} = \frac{\sigma}{666} + 0.60\times\left(\frac{\sigma}{666}\right)^{5} \quad \text{(the base material)}$$

As the simplified model is geometrically symmetrical, merely a quarter of it is investigated. The finite element mesh consists of 490 nodes and 881 right isosceles triangle elements with different sizes. The size of the elements located near the crack tip is smaller than a/360. The elastoplastic parameters in a plane stress condition are calculated by the incremental chord stiffness finite element method with an automatically corrective effect (Ma, 1987).

For the simplified models with a hard layer of different widths, the *J*-integral, opening displacement at the centre of crack σ and load-point-displacement q are calculated by the FEM at each load increment, and these parameters are also estimated in the same remote stress condition by the EPRI approach by using the property of the hard layer material. The results estimated by the EPRI approach are marked by J_{EPRIh}, δ_{EPRIh}, and q_{EPRIh}. The influence of the width of sandwiched hard layer h/2a is shown by comparing the results calculated by the FEM with those obtained by the EPRI approach.

Generally speaking, the path-independence of the *J*-integral defined by Rice will not be maintained for these heterogeneous models, so a modified definition of *J*-integral applicable to heterogeneous layered materials was proposed by (Ma *et al.*, 1988):

$$J = \int_{\Gamma} (w n_1 - n_i \sigma_{ij} u_{j,1}) ds - \sum_{K=1}^{N} \oint_{\phi_K} (w n_1 - n_i \sigma_{ij} u_{j,1}) ds \qquad (1)$$

Where Γ denotes any contour surrounding the crack tip which begins counter clockwise from the under surface of the crack and ends at the upper surface, ϕ_K any counter clockwise closed curve which is within the area surrounded by Γ and passes through two intersecting points of the K-th interface segment and Γ, *n* is the direction cosine of the outward normal to Γ or ϕ_K, ds arc element on Γ or ϕ_K, u_j, the displacement component, σ_{ij} the stress component, and $w = \int \sigma_{ij} d\epsilon_{ij}$ the strain energy density. The path independence of the *J*-integral defined by eqn.(1) has been proved by Ma *et al.* (1988). When the contour is wholly within the sandwiched layer (It means that does not go through the interface between the sandwiched layer and the base material), Eqn.(1) becomes

$$J = \int_{\gamma} (w n_1 - n_i \sigma_{ij} u_{j,1}) ds \qquad (2)$$

which is the original *J*-integral defined by Rice.

For verifying the path-independence of the *J*-integral and obtaining a more precise mean value, in the present study the *J*-integral values are evaluated from Eqn.(1) along nine contours which are different in length, from a/4 to

48a. The original *J*-integral defined by Eqn.(2) is also evaluated to investigate whether it remains path-independent without modification. The procedure for numerically evaluating the *J*-integral defined in eqn.(1) is given by Ma *et al.* (1988). The procedure for estimating parameters J, δ, and q by using the EPRI approach can be found by the EPRI approach (Kumar *et al.*, 1981).

To analyse the crack problem concerning heterogeneous models, a source program is developed by the authors. In the following, it will be indicated that the results calculated by this program coincide with those estimated by the EPRI approach, which shows the correctness of this program and the reliability of the calculated results in the present study.

CALCULATED RESULTS

The *J*-integral is evaluated the modified expression Eqn.(1) along nine contours with different lengths from a/4 to 48a separately. The value integrated along the i-th contour is denoted by as J_i. The relative error Er ($Er=(J_i-J)/J$) to the mean value of the *J-integral* values along the 9 contours, i.e.

$$J=\frac{1}{9}\sum_{i=1}^{9}J_i$$

is within ±4 percent, as shown in Table 1 for the model with h/2a=1.25. These integral contours are shown in Fig.3. Thus the path-independence of the *J*-integral defined by Eqn.(1) is confirmed by the finite element analysis using the incremental plasticity theory. In Table 1, σ is the nominal stress applied on the ends of the model, σ_{ys} is the yield stress of the base material and $\Gamma_1, \Gamma_2, \ldots, \Gamma_9$, represent the nine integral contours respectively. It is shown in Table 2 that the *J*-integral value evaluated from Eqn.(2) instead of the modified expression Eqn.(1) are far from keeping path-independence.

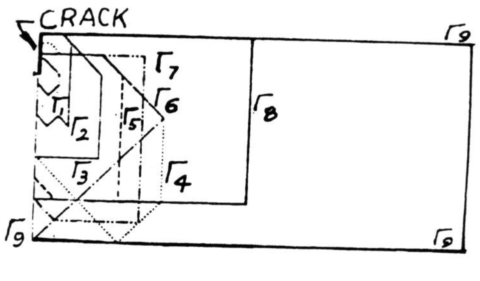


Fig.3. Integral contours.

Table 1. Er(%) calculated by Eqn. (1). h/2a=1.25.

Integral Contour	σ/σ_{ys} 0.03	0.09	0.27	0.55	0.87	1.11	1.31
Γ_1	-1.1	-1.1	-1.5	-1.3	-1.5	0.6	0.1
Γ_2	-1.3	-1.3	-1.7	-1.4	-0.6	2.1	0.8
Γ_3	-1.8	-1.8	-2.3	-2.0	-1.1	1.8	1.0
Γ_4	-3.4	-3.4	-3.5	-3.7	-4.0	-1.5	-0.7
Γ_5	1.9	1.9	2.1	2.0	1.2	0.6	0.8
Γ_6	1.2	1.2	1.5	1.9	1.6	-0.6	-0.6
Γ_7	0.5	0.5	0.7	0.9	0.5	-0.7	0.0
Γ_8	2.0	2.0	2.3	1.9	1.9	-0.9	-0.7
Γ_9	2.0	2.0	2.3	1.7	2.0	-0.8	-0.8

Table 2. Er(%) calculated by Eqn. (2). h/2a=1.25.

Integral Contour	σ/σ_{ys} 0.03	0.09	0.27	0.55	0.87	1.11	1.31
Γ_1	-0.5	-0.5	-0.8	6.3	21.7	35.5	38.8
Γ_2	-0.7	-0.7	-1.0	6.2	22.8	38.3	39.8
Γ_3	-0.8	-0.8	-1.3	5.3	20.7	34.5	33.6
Γ_4	-1.6	-1.6	-2.0	2.8	12.1	20.2	15.9
Γ_5	1.1	1.1	0.7	3.6	6.7	8.1	-0.8
Γ_6	0.6	0.6	0.4	1.4	0.4	-2.0	-10
Γ_7	-0.2	-0.2	-0.4	0.7	0.1	-0.5	-8.0
Γ_8	1.0	1.1	1.7	-7.0	-25	-41	-36
Γ_9	1.0	1.1	2.7	-19	-60	-35	-73

The comparisons of the *J*-integral, opening displacement at the centre of the crack δ and load-point-displacement q calculated by the FEM for heterogeneous models containing a sandwiched layer of different h/2a under various load levels with those estimated by the EPRI approach according to the properties of the hard layer material are shown in Fig.4.

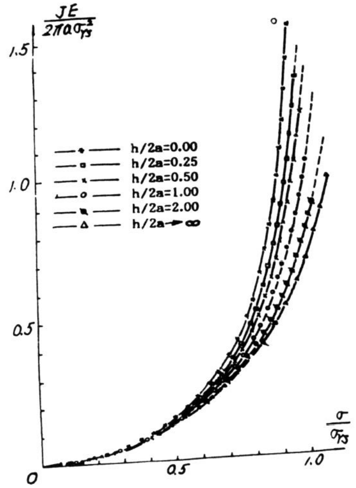
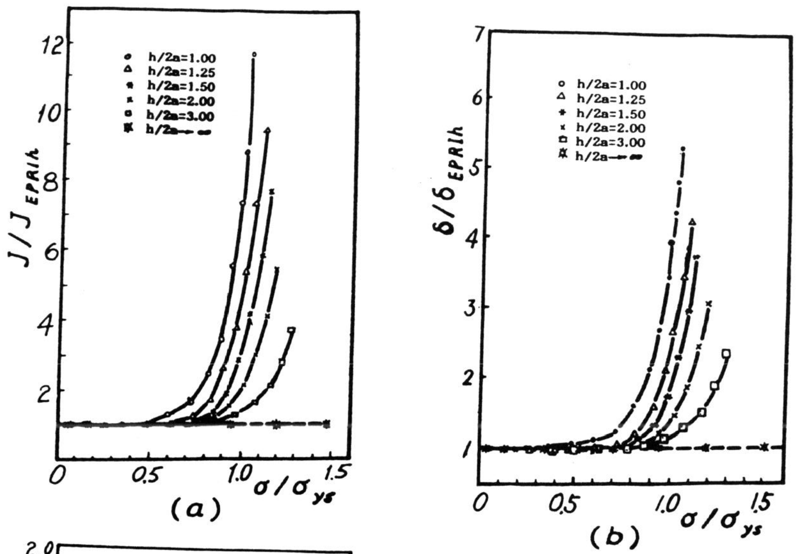


Fig.5. Effect of hard layer width on J-integral. Crack is parallel to interfaces (Ma and Tian, 1986).

It is quite evident that the EPRI approach is not applicable for welded joints with a sandwiched hard layer containing a perpendicular crack in the none-linear stage responding to high load levels, unless it is modified. J/J_{EPRIh}, δ/δ_{EPRIh}, and q/q_{EPRIh} shown in Fig.4 can be regarded as modifying coefficients. It can be found that J/J_{EPRIh}, δ/δ_{EPRIh}, and q/q_{EPRIh} are almost equal to 1 when $h/2a=\infty$ (Fig.4), which show that the FEM program used in present study is correct and the calculated values are believable.

Fig.4 also shows that the effect of hard layer width upon J and δ is similar to that in the model with a sandwiched hard layer containing a parallel crack, which was reported by Ma and Tian (1986) and Tian and Ma (1987) as shown in Fig.5. Within the range of $1 \leq h/2a < \infty$, the smaller is the h/2a, the larger are the values of J or δ, and the higher is the load, the more remarkable is the effect of h/2a.

Combining the results in the present study with those in above Refs., for the models with a sandwiched hard layer containing a parallel crack, it can be deduced that, as far as the crack driving force is concerned, a crack in the hard and narrow region of a welded structure is easier to propagate, and consequently is more dangerous.



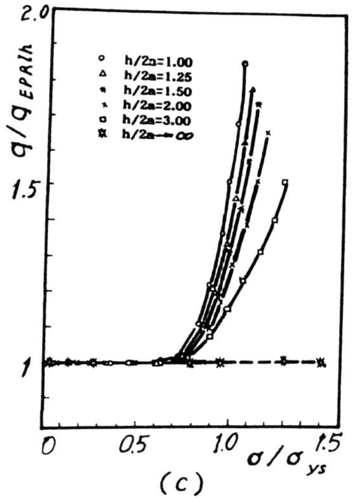


Fig.4. Comparison between J, δ, q and J_{EPRIh}, δ_{EPRIh}, q_{EPRIh}.
(a) $J/J_{EPRIh} - \sigma/\sigma_{ys}$;
(b) $\delta/\delta_{EPRIh} - \sigma/\sigma_{ys}$;
(c) $q/q_{EPRIh} - \sigma/\sigma_{ys}$.
Subscript EPRIh represents the values estimated by EPRI approach corresponding to hard layer. (Plane stress, Normalized, and 2a/W=1/8.)

CONCLUSIONS

After analysing the elastoplastic fracture parameters of welded joints with a sandwiched hard layer containing a perpendicular crack, the following conclusions can be drawn:

1). The path-independence of the modified J-integral for a heterogeneous material crack problem is confirmed.

2). The J-integral, opening displacement at the centre of crack δ, and

load-point-displacement q are affected by the material heterogeneity. The EPRI approach, applicable to homogeneous materials, is not suitable for heterogeneous welded joints, unless it is modified. All the ratios, J/J_{EPRIh}, J/J_{EPRIs}, δ/δ_{EPRIh}, δ/δ_{EPRIs}, q/q_{EPRIh}, and q/q_{EPRIs} given in the present study, can be regarded as modifying coefficients.

3). The effect of mechanical heterogeneity on the value of J-integral and δ is similar to that in the models with a sandwiched hard layer containing a parallel crack. The smaller is h/2a, the larger are J and δ, and the higher is the load, the more remarkable is the effect of h/2a.

4). In regard to the crack driving force, the crack in a hard and narrow brittle zone of welded structures is more dangerous.

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