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THE FINITE ELEMENT SIMULATING CALCULATION OF SURFACE CRACK GROWTH UNDER QUASI-STATIC LOADING IN LBB ASSESSMENT

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ABSTRACT

The prediction of geometric features of surface crack growth under quasi-static loading is recognized as one of the attractive projects in LBB assessment. Since the current fracture criteria do not take variation of actual fracture resistance at the surface crack front into account, the simulating calculation could not predict so good concerning the true geometric features of surface crack growth under quasi-static loading. In this paper, a new fracture criterion of variable fracture resistance, which will consider the actual fracture resistance subjected to diverse stress states, is firstly proposed by authors. Then, the geometric features of surface crack growth are predicted with 3-D finite element simulation. Moreover, the various parameters during crack growth process are calculated simultaneously. The calculated results are in good agreement with experimental values obtained from multi-specimen testing.

1 INTRODUCTION

The prediction of geometric features of surface crack growth under quasi-static loading is recognized as one of the important projects in LBB assessment. Nevertheless, it seems quite difficult not only on setting up an acceptable fracture criterion for simulating calculation of stable 3-D crack growth, but also on the numerical solution of elasto-plastic fracture mechanics by 3-D FEM. The finite element simulating calculation of surface crack growth has ever been reported in Ref [1,2]. But only qualitative results were presented and there was no comparison between calculating results and experimental values owing to the current unsatisfied fracture criteria, which could not reflect the change of actual fracture resistance at the surface crack front. In this paper a new fracture criterion of variable fracture resistance, which will consider the influence of diverse stress states on actual fracture resistance, is firstly proposed by authors. Then, by means of that criterion, the 3-D finite element simulating calculation of local crack growth at the surface crack front are herefrom completed. The various parameters during crack growth process are thus calculated simultaneously. Finally, the quantitative comparison between calculated geometric features of surface crack and the experimental values obtained from multi-specimen testing will be presented in some Charts.

2 THE FRACTURE CRITERION OF VARIABLE FRACTURE RESISTANCE

The phenomenon of different crack fracture resistance under different stress state has been recognized earlier on. But it is still an unsolved problem about how to predict the change of fracture resistance under diverse stress states. According to the condition of J-controlled crack growth, the conventional fracture criterion for stable crack growth could be expressed as:

$$J(a,P) = J_R(\Delta a) \tag{1}$$

In application, the J_R resistance curve subjected to plane strain constraint is usually used for the right term of Eq (1), since it is actually a material constant regardless of the specimen geometry, and is known as a relatively conservative value in engineering assessment.

As regards surface crack, the different points at crack front are subjected to diverse stress states, and will change their stress state during crack growth process. Therefore, by use of Eq (1), the finite element simulating calculation of stable surface crack growth under quasi-static loading could not predict the results correctly. The authors proposed a so called fracture criterion of variable fracture resistance, and a relevant modified resistance curve in following text[3].

Provided that the material resistance curve J_R is measured by single-specimen method under plane strain state, it could be expressed as:

$$J_R = A + B\Delta a \tag{2}$$

where both A and B are material constants; Δa is the crack growth value. Then, the authors' fracture criterion of variable fracture resistance under J-controlled crack growth condition could be written as :

$$J(a,P) = J_{RM}(\Delta a) \tag{3}$$

and

$$J_{RM}(\Delta a) = A + \left(\frac{\Phi_{ex}(\Delta a)}{\Phi(\Delta a)}\right)B\Delta a \tag{4}$$

where Φ is a local constraint factor of triaxial stress state at crack front, which may reflect the effect of different stress state on actual fracture resistance.
The definition of constraint factor is originally defined by McClintock as [4] the ratio of local mean stress σ_m to Mises effective stress σ_{eff} at any point.

In Eq (4) $\Phi_{ex}(\Delta a)$ represents the experimental constraint factor at crack tip of specimen during crack growth. It is actually the corresponding constraint factor of Eq (2) under plane strain states,which is proved to be a material constant[3]. $\Phi(\Delta a)$ is the actual constraint factor at certain local point of crack front corresponding to the variable fracture resistance criterion. Accordingly, from Eq (4) if the stress state at local point satisfies the condition of plane strain constraint, $\Phi(\Delta a) = \Phi_{ex}(\Delta a)$. Hence, Eq(1) is identical with Eq (3), i.e. the variable fracture resistance criterion is consistent with conventional fracture criterion. Otherwise, $\Phi(\Delta a) < \Phi_{ex}(\Delta a)$, it implies that the increment of resistance J_{RM} with respect to the crack growth Δa will be greater than J_R. Thus, Eq (4), which may reflect the crack fracture resistance change under diverse stress state, is defined by authors as modified resistance curve

J_{RM}. By virtue of experimental test and finite element simulating calculation, the modified resistance curve equation of steel 16MnR could be expressed as:

$$J_{RM} = 78.90 + 244.65\triangle a / \Phi(\triangle a) \qquad (5)$$

3 THE METHOD OF SIMULATING CALCULATION OF SURFACE CRACK GROWTH UNDER QUASI-STATIC LOADING

The finite element simulating model is just the same as the steel 16MnR specimen used for the test of stable surface crack growth under quasi-static loading. The elasto-plastic analysis of 3-D finite element is completed by finite element software package PAFEC. The local J-integral at the surface crack front is calculated by 3-D J-integral program compiled by author with virtual crack growth method (VCGM). All study work was implemented on the workstation SUN-III/260 with about 20 hours CPU.

The procedure of finite element simulating calculation of stable surface crack growth under quasi-static loading is described as follows:

Step 1 Set up finite element plate model containing initial surface crack of $a_0 = 5.5$ mm and $c_0 = 16$ mm;

Step 2 Carry on elasto-plastic calculation and solve local J-integral, constraint factor and modified resistance curve at the mid-node of each element along the crack front;

Step 3 Solve crack growth value $\triangle a$ at each point of the crack front in accordance with Eq (5);

Step 4 Make the k-th crack point to propagate a certain value $\triangle a_k$ of crack growth along the orthogonal direction of crack front line. Fit all new points with a smooth curve to get a new surface crack front (Fig 1);

Step 5 Put the calculated local J-integral J_k of the current step to be the re-initiating resistance of crack growth in next step. Then, Eq (5) may be written as

$$J_{RM} = J_k + 244.65\triangle a / \Phi(\triangle a) \ ;$$

Step 6 By means of the new surface crack front mentioned in Step 4, a new finite element model for next cycle could be set up;

Step 7 Repeat Step 2 to Step 6.

4 RESULTS AND ANALYSIS

In this paper, five cycles of finite element simulating calculation corresponding to five loading cases, i.e. $P1 < P2 < P3 < P4 < P5$ respectively have been carried out. The various calculated parameters during crack growth process are shown in Figs 2~4 and listed in Table 1.

The N1~N6 in Figs 2 and 4 as well as the abscissa of Fig 3 represent the calculating points of local J-integral as shown in Fig 1. As illustrated in Fig 3, when loading level rises up to loading case P4 or P5, the maximum value of local J-integral locates at the deepest point N1 of surface crack no more, and will shift to N2 or N3. This result of local J-integral distribution is in good agreement with that in Ref [5] .

The constraint factors corresponding to local J-integral at each calculating point along the surface crack front are given in Table 1. It is obvious that the constraint factors at calculating points N1 and N2 will decrease accompa-

Table 1 The constraint factors Φ (△a) at crack front

Loading case Φ (△a) Cal. pt.	P1	P2	P3	P4	P5
1	1.890	1.866	1.842	1.819	1.771
2	1.860	1.858	1.855	1.853	1.848
3	1.781	1.805	1.829	1.852	1.900
4	1.659	1.705	1.752	1.798	1.891
5	1.470	1.546	1.612	1.697	1.848
6	0.956	1.044	1.133	1.221	1.398

nying with the increase of loading; while at points N3~N6, vice versa. The reason is that the stress state at N1 and N2 will change gradually from plane strain to plane stress so long as the crack propagates up to near penetration, but at other points it is just on the contrary. Moreover, the slope of the modified resistance curve is equal to 244.65/ Φ (△a), then the rate of local crack resistance change at N1 and N2 will increase, while at other points it will decrease in due time. However, the rate of resistance change at N6 is always high enough due to its location of near free surface.

In Fig 1, the solid lines show the geometric features of stable surface crack growth under quasi-static loading calculated by FE simulation; the points (*) and (□) are experimental data under loading cases P1 and P5 respectively. Apparently, they are in good agreement mutually. It implies that under J-controlled crack growth condition the fracture criterion of variable fracture resistance is acceptable to apply for stable surface crack growth, by which the geometric feature of surface crack under quasi-static loading could be well predicted with finite element method.

5 CONCLUSION

5.1 Authors' new fracture criterion of variable fracture resistance is proved to be an effective concept for predicting geometric features of stable surface crack growth under quasi-static loading, which is necessary in LBB assessment.
5.2 The calculated results show that the stress state will influence actual crack fracture resistance. When the surface crack propagates over a/t = 0.5, the location of maximum local J-integral at the crack front will shift beyond the deepest point due to the change of stress state.

6 REFERENCE

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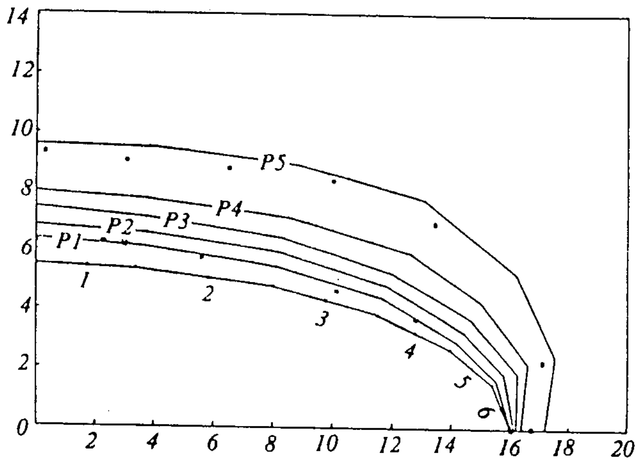

Fig 1 Geometric features of surface crack growth under quasi-static loading

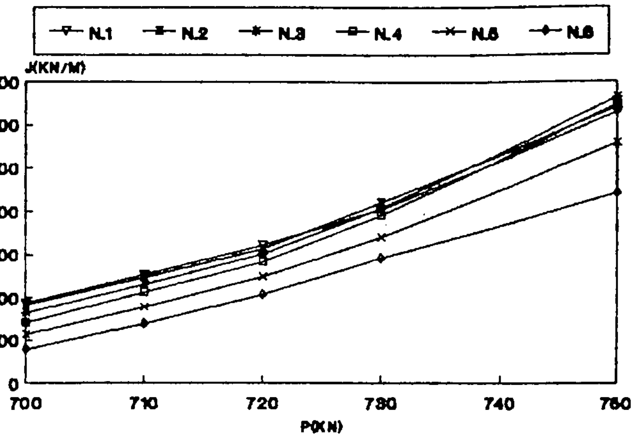

Fig 2 Local J-integral vs loading P

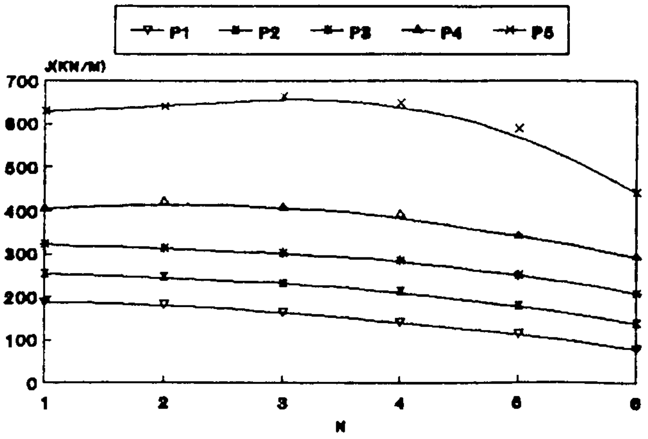

Fig 3 Local J-integral distribution along crack front

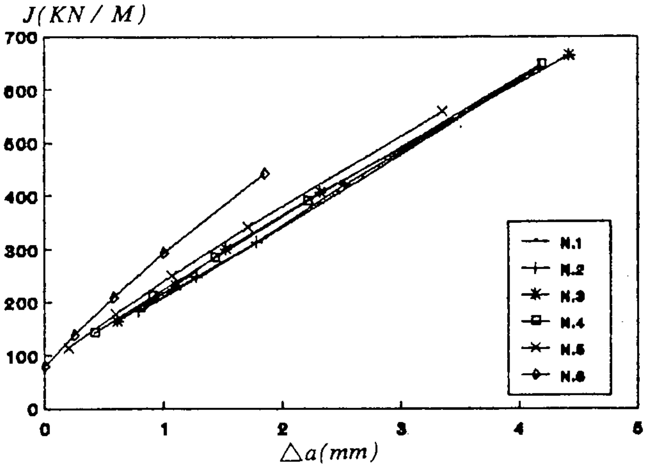

Fig 4 Local J-integral vs crack growth value △a