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Study on Fatigue Propagation of Surface Crack in Metallic Materials

Xinglu Wang*, Kun Zhao, Rui He

School of Vehicle Engineering, Xi'an Aeronautical University, Xi'an 710077, China
**Corresponding Author*

ABSTRACT. *Aiming at the phenomenon of fracture failure caused by surface crack propagation in metal structures, a novel calculation method for shape evolution of surface crack growth is proposed considering crack closure effects. The functional relationship between shape parameters of surface crack in plate under fatigue loads is calculated by the novel calculation method, and the surface crack propagation shape evolution is simulated by the calculation results. Surface crack growth experiments in plate is carried out, the experiments results are compared with calculated results. The test results are basically identical with calculation results, which shows that the method based on energy release rate is effective for calculate shape evolution of surface crack.*

KEYWORDS: *Surface Crack Propagation, Shape Evolution, Energy Release Rate, Stress Intensity Factor, Metal Structures*

1. Introduction

Fracture failure of metal structures gradually increase with the extension of service time, and surface crack is the main factor that induces the structural fracture and seriously affects the structures' carrying capacity and fatigue strength[1]. Newman and Raju[2] assumed that surface crack maintains semi-elliptical shape during the whole propagation, but the aspect ratio of semi-elliptical is changing with surface crack growth. The crack shape determines the distribution of stress field and the size of the stress intensity factor at the crack front, which affects the fatigue strength calculation and fatigue life prediction of metal structures. A large number of researchers are concerning about the shape evolution of surface crack propagation[3,4].

Newman and Raju estimated the growth increments using the Paris law simply at the surface and deepest point of surface crack. McFadyen measured the shape evolution of surface cracks propagation and predicted the change of aspect ratio by Newman and Raju's approach. Hou developed a free-front finite element technique to simulate the surface crack shape evolution considering the crack closure effects. Shi and Cai[5] proposed a theoretical model of semi-elliptic surface crack growth combined with the Newman-Raju formula. The current methods are mainly based on empirical formulas and finite elements method, and they applied only to simple structures. A novel calculation method for aspect ratio evolution of surface crack propagation is put forward on the basis of the energy release rate, the shape evolution of surface crack propagation in plate and welding T-joint are studied respectively. Finally, experiments are carried out to verify the method.

2. Calculation method

2.1 The Relationship between Energy Release Rate and Stress Intensity Factor

Irwin[6] proposed the energy release rate first, which used to represent the energy released as crack growth per unite area. Both the energy theory and the stress intensity factor theory are solving the problems of crack propagation under linear elastic condition, and the relationship between the two theories is given in fracture mechanics.

$$G = \frac{K_I^2}{E'} \tag{1}$$

Where G is energy release rate, K_I is model I stress intensity factor, E' is equivalence material elastic modulus, $E' = E$ (plane stress condition), $E' = E/\left(1-\upsilon^2\right)$ (plane strain condition), E is material elastic modulus and υ is Poisson’s ratio.

2.2 Crack closure

Elber found the phenomenon of crack closure in crack propagation experiment, and suggested that using effective stress intensity factor as driving force for crack propagation. Plastic induced crack closure theory is currently accepted explanation for crack closure phenomenon. Parameter U called opening ratio is introduced to express the influence of crack closure on crack propagation. Song and Shieh measured the crack closure behavior of surface cracks and found that the closure slowed down the crack growth rate[7]. The upper and lower surfaces of crack contacted because of material plastic deformation in crack tip region, and the crack must be fully open.

$$U = \frac{\Delta K_{\mathrm{eff}}}{\Delta K} = \frac{K_{\max} - K_{op}}{K_{\max} - K_{\min}} \tag{2}$$

Where ΔK_{eff} is effective stress intensity factor range, ΔK is stress intensity factor range, $K_{\max}$ is maximum stress intensity factor, K_{op} is opening stress intensity factor and $K_{\min}$ is minimum stress intensity factor.

ISSN 2616-5767 Vol.3, Issue 6: 67-74, DOI: 10.25236/AJETS.2020.030608

$$\Delta K_{\text{eff}} = UK_{\max}(1-R) \tag{3}$$

Where R is stress ratio.

2.3 Effective energy release rate

Taking effective stress intensity factor as driving force, effective energy release G_{eff} is given as follows.

$$G_{\text{eff}} = \frac{\Delta K_{\text{eff}}^2}{E'} \tag{4}$$

2.4 Calculation for shape evolution of surface crack propagation

The semi-ellipse surface crack is shown in Fig.1. A is the deepest point and C is the surface point, a and c are the shape parameters of semi-ellipse surface crack.

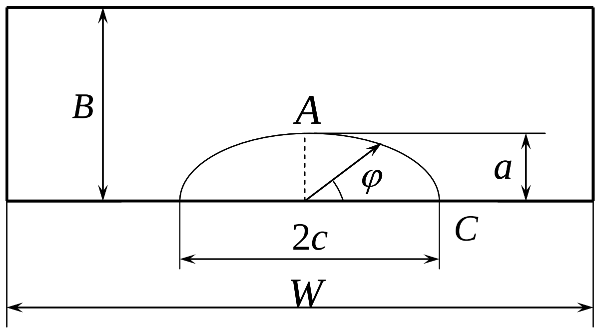


Figure. 1 Semi-ellipse surface crack

The effective energy release rate of every point on the front of crack tip is equal when crack propagation. Therefore, the effective energy release rate at the deepest point A and the surface point C of semi-ellipse surface crack must be equal.

$$G_{A\text{eff}} = G_{C\text{eff}} \tag{5}$$

$$U_A^2 K_{A\max}^2 E_C' = U_C^2 K_{C\max}^2 E_A' \tag{6}$$

Where U_A is opening ratio at point A, U_C is opening ratio at point C, $K_{A\max}$ is maximum stress intensity factor at point A, $K_{C\max}$ is maximum stress intensity factor at C, E_A' is equivalent material elastic modulus at point A, E_C' is equivalent material elastic modulus at point C.

Surface point C is in plane stress state and deepest point A is in plane strain state under external load.

$$E'_A = \frac{E}{1-\upsilon^2},\ E'_C = E \tag{7}$$

The ratio of opening ratio at surface point C to opening ratio at deepest point A is approximately 0.9[8].

$$U_C / U_A \approx 0.9 \tag{8}$$

Substituting equations (7) and (8) for equation (6).

$$\left(1-\upsilon^2\right) K_{A\max}^2 = 0.81 K_{C\max}^2 \tag{9}$$

For the semi-elliptical surface crack in metal structures, stress intensity factor K is a function of aspect ratio a/c and depth ratio a/B, the functional relationship between a/c and a/B is obtained by substituting the expression of stress intensity factor for equation (9). For a certain thickness B of plate, c is changing with the change of a, this relationship is used to describe the shape variation during surface crack propagation.

Therefore, when solving the shape evolution of surface crack propagation in different structures, it only needs to solve the max stress intensity factor at point A and C of surface crack, substitute them and Poisson's ratio for equation (9), the calculation method is simple.

3. Surface crack propagation shape analyses

Micro defects are easy formed in plate surface with the affect factors of processing and installation, this micro defects are taken as initial surface crack and propagates gradually, finally resulting in structures fracture failure.

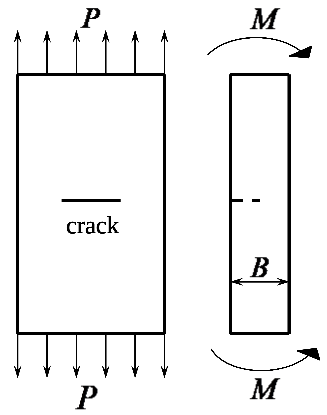
3.1 Overall structure design of the intelligent workshop product

Force diagram for plate with surface crack is shown in Fig.2, plate under tensile load in figure 2(a) and pure bending in figure 2(b), structures will suffer tensile load and bending load at the same time in actual working conditions. Mode I stress intensity factor plays a leading role in the progress of surface crack propagation and it can be expressed as follows[9].

$$K_I = \left(\sigma_t + H\sigma_b\right)\frac{\sqrt{\pi a}}{\Phi} F\left(\frac{a}{c}, \frac{a}{B}, \frac{2c}{W}, \varphi\right) \tag{10}$$

ISSN 2616-5767 Vol.3, Issue 6: 67-74, DOI: 10.25236/AJETS.2020.030608

Where σ_t is tensile stress, σ_b is bending stress, a/c is aspect ratio, a/B is depth ratio, W is plate width, φ is parameters Angle for surface crack, and Φ is half elliptic integral.

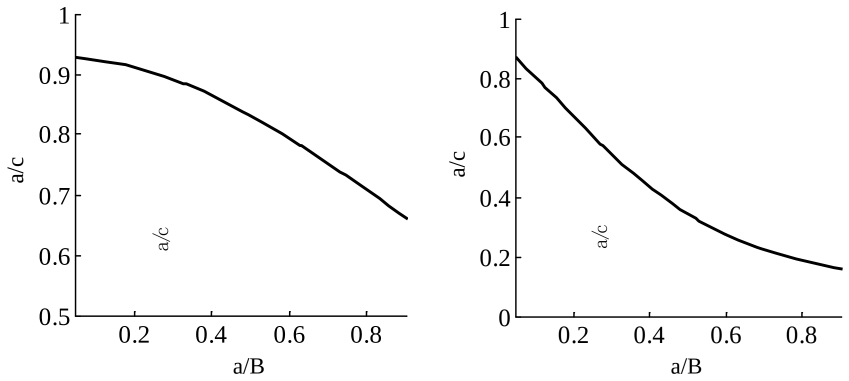


(a) Tension (b) bending

Figure. 2 Force diagram for plate with surface crack

3.2 Calculation results and analysis

Aspect ratio variation of Semi-elliptical surface crack is calculated by the method proposed in section 2. The calculation results are shown in Fig.3, there are large difference between the two kinds of shape evolution when they under tensile load and pure bending load respectively.

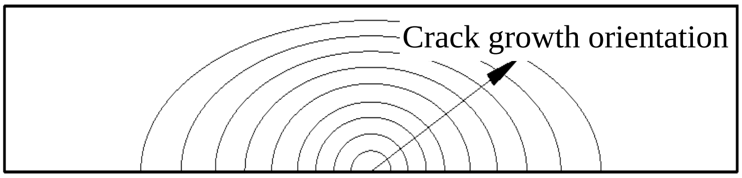


(a) Tension *(b) Bending*

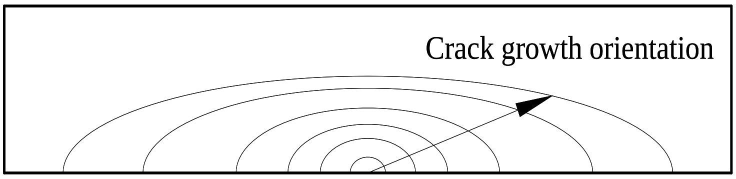
Figure. 3 Aspect ratio variation in plate

ISSN 2616-5767 Vol.3, Issue 6: 67-74, DOI: 10.25236/AJETS.2020.030608

In figure 3(a), plate with surface crack under tensile load, a/c is close to 1 in the initial stage, the shape of surface crack appears as semicircular, the value of a/c decreases gradually with the crack propagation and the shape of surface crack appears as semi-ellipse, a/c is close to 0.6 at fracture. In figure 3(b), plate with surface crack under pure bending load, a/c is close to 0.9 in the initial stage, the value of a/c decreases rapidly with the crack propagation and the shape of surface crack appears as slender semi-ellipse, a/c is close to 0.2 at fracture. Surface crack growth shape in plate under tension and pure bending are simulated respectively on the basis of calculation results, and the simulation results are shown in Fig.4. The shapes of surface crack propagation are totally different under two different load cases.



(a) Tension



(b) Bending

Figure. 4 Shape of surface crack growth in plate

3.3 Test result

Taking 10mm thick plate for example, one semi-ellipse surface crack ($a = 2mm$, $2c = 8mm$) is prefabricated by spark erosion technique. Two ends of the plate specimen are respectively clamped in the upper clamping head and lower clamping head, as shown in Fig.5. Test load parameters are installed as follows: sine form load, stress ratio is 0.1, average stress is 11KN and frequency is 10Hz.

ISSN 2616-5767 Vol.3, Issue 6: 67-74, DOI: 10.25236/AJETS.2020.030608

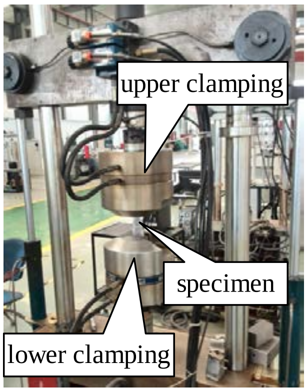


Figure. 5 Plate experiment

Surface crack propagation shape development testing is proceeded. Cutting the load amplitude in half when find the prefabricated surface crack begin to propagation, specimen under the lower amplitude load until fracture. take the crack front curve compare with the curve obtained by calculation as shown in figure 4(a). The contrast analysis results are shown in Fig.6.

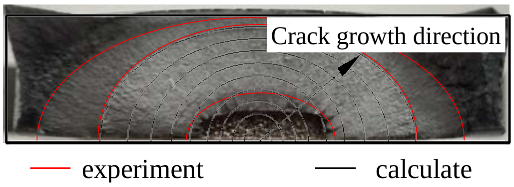


Figure. 6 Comparison results

There are large gaps between two kinds of crack front curve at the initial stage of surface crack growth, due to the influence of initial crack shape. The experimented crack front curve is close to the calculated crack front curve gradually in the progress of surface crack growth, when the crack extends to a certain degree, two kinds of crack front curve obtained by different methods are basically tallies. It is effective for the proposed method to calculate the surface crack shape evolution.

4. Conclusion

In the present paper, the shape evolution behavior of surface crack propagation has been numerically and experimentally analyzed.

(1) A novel method used to calculate the shape evolution of surface crack propagation is proposed based on the energy release rate.

ISSN 2616-5767 Vol.3, Issue 6: 67-74, DOI: 10.25236/AJETS.2020.030608

(2) The function relationship between shape parameters of surface crack in plate is calculated respectively by the novel method, and the surface crack shape is simulated from initial crack to fracture.

(3) Experimental research of surface crack propagation is conducted, and the experimental results are well in agreement with the theoretical results, which prove that the method to calculate shape evolution of surface crack propagation based on energy release rate is correct.

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