第I部門

Effect of Cyclic Plasticity and Deformation History on Short Crack`s CTOD$_p$ Distribution in Thickness

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1. Introduction

Fatigue of metal materials is a major cause of failure in engineering structures. Investigating fatigue crack growth (FCG) behavior in materials is particularly significant for understanding fatigue failure of structures. Various parameters, such as stress intensity factors, J-integral, crack-tip strain, crack-tip plastic zone size, and crack-tip opening displacement (CTOD), have been proposed as correlations to FCG rates (i.e., da/dN) of materials. [1)]

With ease of measurement and clear physical meaning, CTOD has been extensively studied in both experimentally and numerically. Crack closure is a phenomenon that consists of contact between fracture surfaces during a portion of load cycles. This contact affects local stress and plastic deformation fields near crack tip, and thus micro mechanisms are responsible for fatigue propagation. CTOD$_p$ is plastic part of CTOD in loading and unloading process. In this study, CTOD and CTOD$_p$ considering crack closure and plate thickness is examined for crack propagation assessment, based on finite element (FEM) models that had been established and calibrated using experiment results.

2. Experiment and finite element model

Fig. 1 shows configuration of SENT specimen made of SM490 steel used in fatigue test.

Fatigue test was conducted using a Serve Hydraulic Testing Machine with a load capacity of 20 KN. The specimen underwent tensile loading cycles at applied load ranged from 0.693 kN to 6.93 kN, resulting in loading condition of σ_{min} = 11 MPa, σ_{max} = 110 MPa stress ratio R = 0.1, within a load frequency of 16 Hz sinusoidal wave. To monitor behaviors of specimen during chucking and testing stages, an uniaxial strain gauge with a grid size of 1 mm by 2 mm was attached as Fig.1. In addition, Digital Image Correlation (DIC) technique was utilized to obtain displacement and strain field around notch and to identify fatigue crack length at a certain number of loading cycles.

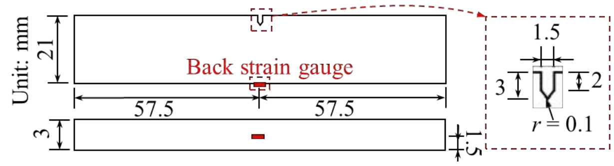

Fig.1 Geometry of SENT specimen.

As Fig. 2, a finite element model was constructed using 1/4 of physical model, leveraging symmetry. FEM meshes comprised 2 primary regions utilizing C3D8 element: a refined mesh of approximately 5 μm in crack propagation region and a coarser mesh extending up to 2.5 mm in remaining volume with 10 layers in thickness. Contact between crack flanks was modeled by considering a rigid body aligned with crack symmetry plane. A fatigue SS model was applied in the FEM analysis. [2)]

Fig.3 shows comparison of experiments and simulations. Back-gauge strain and notch displacement are in good compliance when crack length a = 0 mm. In crack length a = 0 mm, a DIC elongation gauge in 3 mm was chosen to extract displacement. As Fig.3 (c) and (d), for thickness 1 mm and 3mm, in a = 0.4, 1.5, 3 mm, same DIC elongation gauge in 0.2 mm was used to measure CTOD, and crack closure was found in all measured condition, which enhanced significance of crack closure effects on crack propagation assessment.

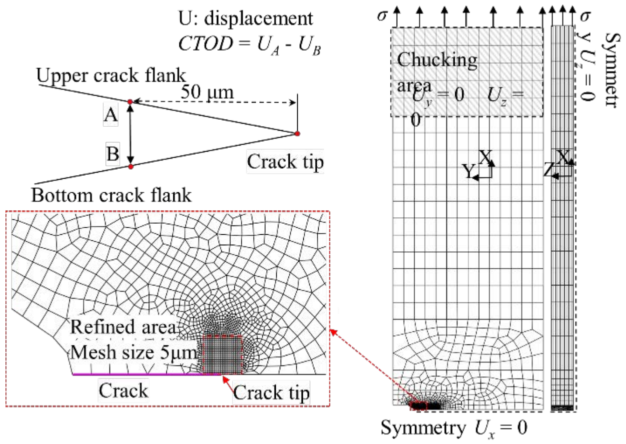

Fig.2 Finite element model of SENT specimen.

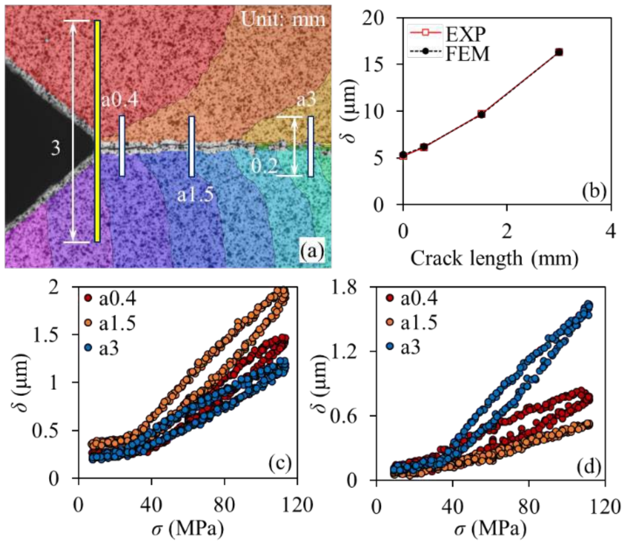

Fig.3 FEM correction and crack closure effect

3. Simulation results

To consider deformation history, crack propagate from 0 μm to 50 μm to accumulate plasticity in per increment 5 μm. Fig.4 (a) shows flow to extract plastic CTOD in loading and unloading process. Fig.4 (b) plots displacement in notch node when crack propagate from 0 μm to 50 μm in different NLC (number of load cycles in every increment). δ_{notch}(Displacement in notch) range keeps the same even NLC becomes larger.

In Fig.4 (c), NLC was chosen in 2 cycle per increment. Results in unloading process with deformation history and initial 2 cycles in crack length 0 μm, with deformation history but no initial 2 cycles and no deformation history result are compared. With deformation history, crack closure effect happens due to plasticity accumulation around minimum load force.

Fig.4 (d) shows *CTOD* range and $CTOD_p$ range in unloading process when crack propagate from 0 μm to 50 μm and 100 μm. In analytical, surface is more close to plane stress condition while center part is more close to plane strain. Thus, across thickness direction, $CTOD_p$ range is larger in surface due to weaker constraint. And *CTOD* range contains more elastic part like Fig.4 (a), so surface *CTOD* range is smaller due to more severe plasticity accumulation and less elastic displacement, which is in compliance with real crack front shape.

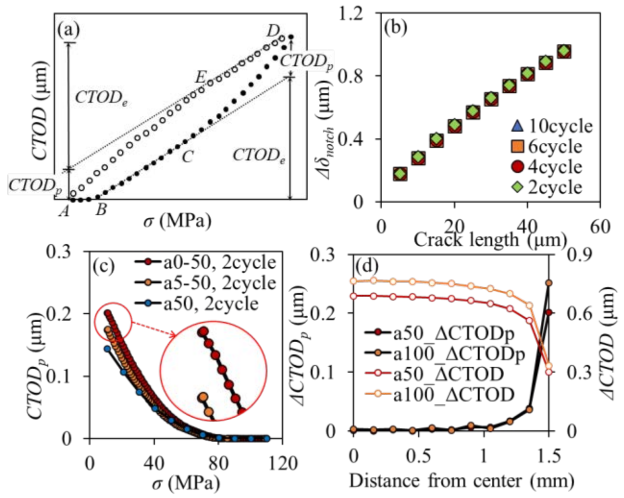

Fig.4 Analytical process and numerical results

4. Conclusion

Crack closure effect was measured in small and long crack, and FEM corrected by experiments shows crack closure effect successfully. For modeling method functioned with crack propagation rate, CTOD is more consistent with crack front geometry than plastic CTOD.

Reference

1)Stephens, R. I., Fatemi, A., Stephens, R. R., & Fuchs, H. O. (2000). Metal fatigue in engineering. John Wiley & Sons.

2)Fincato, R., Yonezawa, T. & Tsutsumi, S., Numerical modeling of cyclic softening/hardening behavior of carbon steels from low- to high-cycle fatigue regime. Archiv.Civ.Mech.Eng, 23, 164 (2023).