A STUDY ON THE EFFECT OF RESIDUAL STRESS ON FATIGUE BEHAVIOR

Seung-Yong Yang*, Byeongchoon Goo *
*National Research Lab., Korea Railroad Research Institute, Uiwang-City, 437-050, Korea

Summary The effect of residual stress on fatigue crack growth was investigated in terms of finite element analysis. Simulations were performed on a CT specimen in plane strain. An interface-cohesive element that accounts for damage accumulation due to fatigue along the notch direction has been used. Numerical results show that fatigue crack growth rate slows down when compressive residual stress field exists in front of the crack tip.

INTRODUCTION

To extend the life time of metallic structures under fatigue loading, several methods have been tried, for example extending the time period of crack nucleation or repairing whole sections containing cracks fully penetrating through the thickness, etc. Song [1] has proposed to generate compressive residual stress around the crack tip by local heating to delay or stop the fatigue crack growth. Procedures using S-N and ε-N curves are widely being used as criteria for fatigue design.[2] In this paper, we directly simulate the fatigue crack growth by finite element method using a cohesive surface model. The effect of residual stress on delaying fatigue crack growth was investigated. Analyses were performed on a compact tension (CT) specimen in plane strain. The calculations are carried out on the commercial finite element code ABAQUS.
Several cohesive zone models have been suggested to simulate fatigue crack growth [3-4]. In [3], the traction-displacement behavior did not follow a predefined path, but cohesive properties were degraded as damage accumulates due to cyclic loading. In [4], an irreversible cohesive law with unloading-reloading hysteresis was used in finite element analysis to explain experimental observation. The same type of damage evolution law as in [3] was used in our work. The results showed fatigue crack growth slows down with compressive residual stress distribution around the crack tip.

RESIDUAL STRESS BY LOCAL HEATING

Before describing the constitutive laws of the cohesive zone model, we briefly summarize the generation of residual stress by local heating. Fig. 1 shows the plane strain finite element model used to simulate the heating procedure. The height of the model is 75mm, the distance between the notch and the right hand side boundary is 100mm, and symmetric boundary conditions were imposed on the AB line. Heat input of 368 MJ/m^2s is applied on the surface of the elements along the CD line moving downward with speed of 2.42 mm/s. The maximum temperature of the specimen increased up to 1500 ^oC. Thermo mechanical finite element calculation was performed to obtain the resultant residual stress.

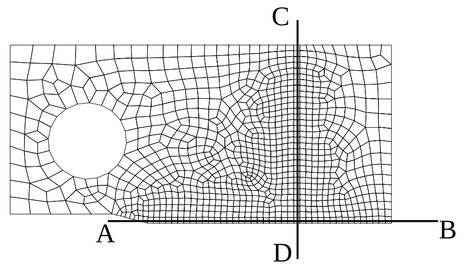

Fig. 1. Finite element mesh for CT specimen.

The cohesive surfaces are embedded along the line AB, and the surrounding volume undergoes elastic-plastic deformation. Changes of thermal and mechanical properties with temperature were considered in the analysis. The yielding strength at room temperature is 250MPa, and decreases to 0MPa at 1200 ^oC. Fig. 2(a) illustrates the distribution of vertical component σ_{yy} of the residual stress. One can observe that compressive stress distributes between the notch and the heating line. The maximum level of the tensile stress approaches to the yielding stress.

SIMULATION OF FATIGUE CRACK GROWTH

In this section, a brief description of the cohesive surface model is given, as the framework of the model is already well known by many researchers. The irreversible effective traction-displacement relation in [4] is used combined with the damage evolution equation given in [3] to account for the degradation of the cohesive strength due to fatigue. In this way, fatigue crack growth can be simulated directly without explicitly specifying crack growth criterion. Meanwhile, for normal contact compression, an effective displacement is defined only with the sliding component of the material separation, and the corresponding normal traction is assumed to behave as a linear spring with respect to the normal displacement. The initial cohesive strength was set to 1000MPa, the endurance limit was 150MPa, and the characteristic length parameter δ_c was 50 μm. Cyclic load of 5MN with period 2s is applied. Fig. 2(b) illustrates redistributed vertical residual stress after the crack tip propagates from the notch to the location marked by arrow after 100 cycles. The amount of stress relaxation is not severe since the stress is compressive on the crack face. In this simulation of crack growth, the mesh size Δx of the interface-cohesive element is the same as in Fig. 1 (Δx =2500 μm), but convergent results were obtained compared with results from much finer model (Δx =200 μ m), and the mesh dependence of solution was not strong.

Fatigue crack growth rate vs. Δ K behaviour is drawn in Fig. 3 for the cases with and without the compressive residual stress. The stress intensity range Δ K was calculated from the specimen without residual stress, and the speed of crack growth was calculated from the simulation results in each case. We can observe that the crack growth rate slows down when compressive stress field exists in front of the crack tip. Meanwhile, the numerically predicted data without residual stress can be fitted to a Paris type power law $da/dN=C\Delta K^n$ with n=3.32.

Bye the way, the material parameters for the cohesive interface were presumed approximately, and they need to be calibrated by comparing with experimental works.

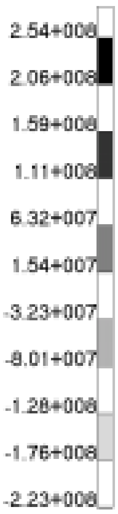

Fig. 2(a). Residual stress distribution by local heating.

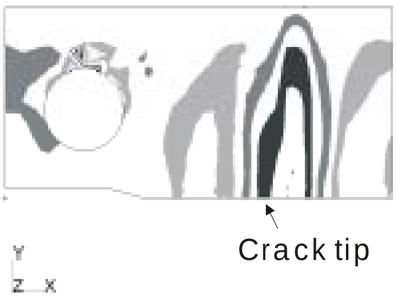

Fig. 2(b). Residual stress distribution after cyclic loading. The current location of the crack tip is denoted by arrow.

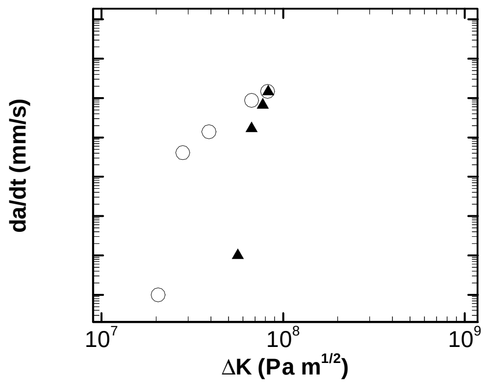

Fig. 3. Numerical fatigue crack growth rates with and without residual stress. Circles are results without residual stress, and triangles are results with residual stress.

CONCLUSIONS

The effect of residual stress on fatigue behaviour was investigated by finite element method incorporating a cohesive zone model with evolutionary damage law. Fatigue crack propagation was simulated for two-dimensional cases with and without compressive residual stress. The following conclusions can be made from the numerical study.

1. When compressive residual stress normal to the crack surface exists around the crack tip, the fatigue crack growth rate is reduced.
2. As the fatigue crack propagates, residual stress is redistributed.

Acknowledgement

This work was supported by the National Research Laboratory (NRL) program of the Korea Ministry of Science and Technology.

References

[1] Song, H.C.: Fatigue Life Extension of Steel Plates with a Through-the-Thickness Crack Using Local Heating. *PhD Thesis*, Seoul National University, 2001.

[2] Stephens, R., et al.: Metal Fatigue in Engineering. John Wiley & Sons, Inc., 2000.

[3] Roe, K.L. and Siegmund, T.: An Irreversible Cohesive Zone Model for Interface Fatigue Crack Growth. *Engineering Fracture Mech.* **70**:209-232, 2003.

[4] De-Andres, A. and Perez, J.L. and Ortiz, M.: Elastoplastic finite element analysis of three-dimensional fatigue crack growth in aluminum shafts subjected to axial loading. *Int. J. Solids & Structures* **36**:2231-2258, 1999.