CRYSTAL PLSTICITY MODELING OF FATIGUE CRACK GROWTH IN STAINLESS STEEL

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Abstract

Predicting the crack behavior under monotonic and cyclic loading is essential for an accurate assessment of the reliability of engineering structures. This work is concerned with the deformation fields in crack tip grains and their effects on fatigue crack growth rates under cyclic loading. We develop a cyclic crystal plasticity finite element (CPFE) model to characterize the mechanical behavior of 316L stainless steel. The deformation fields in crystal grains near crack tips under monotonic and cyclic loading are studied for two crack tip grain orientations using CPFE simulations. The CPFE results under monotonic loading are consistent with previous theoretical and experimental results. The CPFE results under cyclic loading match those from cyclic J2 plasticity finite element (JPFE) simulations. Based on the accumulated plastic work, cyclic CPFE simulations predict the fatigue crack growth rate as a function of stress intensity factor. The predicted Paris law exponent is consistent with the experimental value. This work demonstrates a new CPFE approach to predict both the deformation field and fatigue crack growth rate in metal alloys. This approach may be further generalized to investigate the time dependent crack growth that can be strongly influenced by the crystallographic effects of crack tip grains.

1. Introduction

Fatigue crack growth is a common mode of failure in metal alloys under cyclic loading. The rate of fatigue crack growth is often used to predict fatigue life in engineering applications. Recent theoretical predictions of the fatigue crack growth rate account for realistic cyclic plasticity responses by including the kinematic hardening and Bauschinger effects [1]. However, the impact of crystallographic effects of crack tip grains on the fatigue crack growth rate remains largely unexplored by computational modeling. On the other hand, crack tip deformation fields in single crystals and polycrystals have been studied by experiment, theoretical analysis and computational modeling in the past. However, the results and insights from these studies have not been effectively used to inform the computational modeling of fatigue crack growth rate in metal alloys.

2. Results

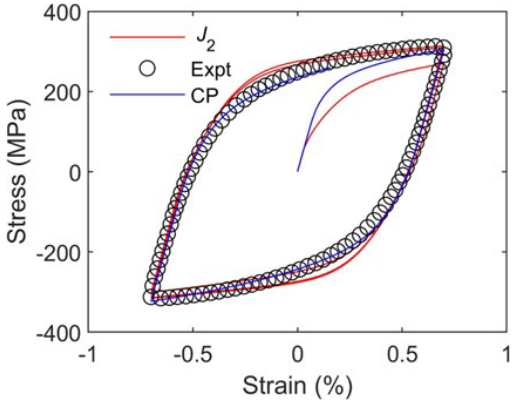

Fig.1 – Comparison of uniaxial stress-strain hysteresis loops from experimental measurement [2], cyclic CPFE and JPFE simulations for 316L stainless steel under strain-controlled cyclic loading.

In this work, both the CPFE and JPFE models are used to simulate the mechanical behavior of polycrystalline 316L stainless steel. The cyclic stress-strain data are taken from the experiment by Pham et al. [2] at a strain rate of 10^{-3} /s for a strain amplitude of ±0.7%. Fig. 1 shows that the predicted cyclic stress-strain curves by the CPFE and JPFE models are in close agreement with the experimentally measured stable hysteresis loop of 316L stainless steel.

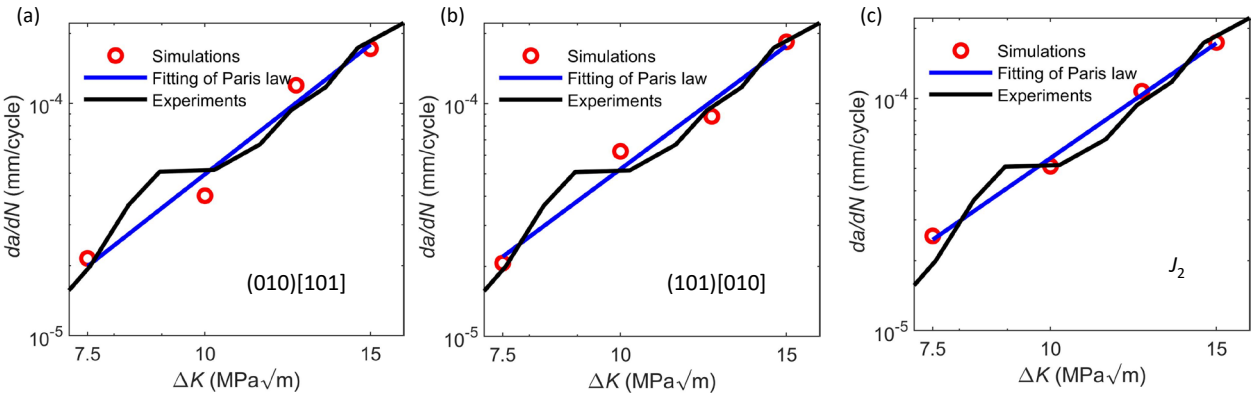

Fig. 2 – Predicted fatigue crack growth rate da/dN vs. stress intensity range ΔK (circles) with the fitting Paris law curve (blue line), as compared with the experimental Paris law curve [3] (black line). (a) Cyclic CPFE results for the (010)[101] crack. (b) Cyclic CPFE results for the (101)[010] crack. (c) Cyclic JPFE results.

Fig. 2 shows comparison of the fatigue crack growth rate da/dN vs. ΔK between experimental measurements [3] and predictions by cyclic CPFE simulations for two crack orientations as well as by cyclic JPFE simulations. As seen from Fig. 2, our simulation results are in good agreement with experimental data. The predicted Paris law behavior of fatigue crack growth is shown by the approximate linear relation between da/dN vs. ΔK in the log-log plot. Correspondingly, the predicted Paris exponent *m* is 3.17 and 3.00 for the two crack orientations by CPFE simulations and 2.81 by JPFE simulations. Compared to the JPFE results, the CPFE-predicted *m* values are closer to the experimentally measured *m* values of 2.91 and 3.27 at testing frequencies of 0.0015 Hz and 1.5 Hz, respectively [3]. The closer agreement between CPFE predictions and experimental measurements indicate that cyclic CPFE simulations can capture the important crystallographic effects of plastic slip near crack tips and thus improve prediction of the Paris exponent *m*.

3. Conclusions

The CPFE model can effectively represents major factors controlling the deformation fields in crystal grains at a crack tip, including elastic and plastic anisotropy, finite strain and finite lattice rotation, and kinematic hardening. The cyclic CPFE simulations can improved the accuracy of prediction of the fatigue crack growth rate in stainless steel. The CPFE approach developed may be further generalized to investigate the time dependent crack growth that can be strongly influenced by the crystallographic effects of crack tip grains.

References

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