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Microstructure-sensitive small fatigue crack growth assessment: Effect of strain ratio, multiaxial strain state, and geometric discontinuities

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ABSTRACT

Fatigue crack initiation in the high cycle fatigue regime is strongly influenced by microstructural features. Research efforts have usually focused on predicting fatigue resistance against crack incubation without considering the early fatigue crack growth after encountering the first grain boundary. However, a significant fraction of the variability of the total fatigue life can be attributed to growth of small cracks as they encounter the first few grain boundaries, rather than crack formation within the first grain. This paper builds on the framework previously developed by the authors to assess microstructure-sensitive small fatigue crack formation and early growth under complex loading conditions. The scheme employs finite element simulations that explicitly render grains and crystallographic directions along with simulation of microstructurally small fatigue crack growth from grain to grain. The methodology employs a crystal plasticity algorithm in ABAQUS that was previously calibrated to study fatigue crack initiation in RR1000 Ni-base superalloy. This work present simulations with non-zero applied mean strains and geometric discontinuities that were not previously considered for calibration. Results exhibit trends similar to those found in experiments for multiple metallic materials, conveying a consistent physical description of fatigue damage phenomena.

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1. Introduction

Fatigue failure in the high cycle regime is dominated by the formation and early growth of cracks that meander through the microstructure. Multiple approaches have been proposed to consider a crack initiation length, but such a definition is typically valid for a specific material and loading conditions, the range of lengths that can be detected, and the nature of the crack initiation criterion employed. Nevertheless, it is believed that for engineering metals, the crack formation process—nucleation and early growth—concludes after cracking an area corresponding roughly to several (i.e., two to ten) mean grain diameters; this typically implies cracking tens to hundreds of individual grains. Once the crack has reached this size, the crack front effectively samples enough grains to smear out the microstructural variability, thereby attaining similitude conditions necessary for application of long crack linear or elasto-plastic fracture mechanics (LEFM or EPFM, respectively). The number of grains required along the crack front to reach this condition depends both on crack geometry and loading conditions. Furthermore, we found [1] that a significant fraction of the variability of total fatigue life can be attributed to small cracks encountering and crossing the first few grain boundaries, rather than fatigue crack formation within the first grain.

Most modeling approaches have either focused on assessing the nucleation process considering intrinsic microstructure variability without fatigue crack growth; however, limited modeling efforts have focused on small crack growth though the microstructure, e.g., estimating the number of cycles required to grow a crack through the first few grains. Exceptions can be found in the work by Krupp and coworkers [2–4], primarily addressing two-dimensional representations. More recently, we [1,5] developed a three-dimensional modeling scheme to estimate the early fatigue life for crystallographic (Stage I) fatigue crack growth across multiple grains. This approach estimates the fatigue life by assessing nonlocal Fatigue Indicator Parameters (FIPs) [6,7] that serve as surrogate measures for small crack driving force as expressed by the range of mixed mode cyclic crack tip displacement. Furthermore, cracks are propagated along crystallographic planes by degrading the elastic stiffness that respects restoration of elastic stiffness during roughness- or plasticity-induced crack closure. The approach is implicitly valid for multiaxial loading conditions,

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thereby avoiding the need for assignment of mesoscopic multiaxial fatigue criteria at the scale of many grains.

One of the main deficiencies of fatigue models is the introduction of fitting coefficients that do not have physical interpretation. These approaches pose a risk when exercising the model for loading conditions and materials systems different from those used for calibration. This work expands our previous efforts and applies those methodologies to multiple multiaxial loading conditions and geometries without changing any physical parameter. The objective of this paper is to assess whether the framework presented and calibrated in previous publications is adequate for loading conditions different from those used for calibration. In particular, we propose to assess the role on early fatigue life of the applied strain ratio (that induce different mean stresses) and geometrical discontinuities (e.g., holes, notches).

Given the large number of parameters in crystal plasticity approaches (which are not uniquely defined), there is value in assessing capability to predict fatigue trends as opposed to refining coefficients to match fatigue response of a single material. In other words, we seek to assess general model capabilities to predict experimentally observed trends, rather than pursuing detailed correlation with a fatigue dataset for one material. We argue that the agreement between simulations for a given set of model parameters and well-established trends of fatigue behavior is useful to assess the viability of a model to reflect the physics of formation and growth of microstructurally small cracks (MSCs) in polycrystalline microstructures.

2. Experimental observations and general trends

Our objective is to evaluate the capability of a microstructure-sensitive computational fatigue modeling framework to represent well-established trends in fatigue response observed across multiple material systems and loading conditions. Therefore, this section summarizes a few general aspects of fatigue crack formation and early growth (i.e., early stage crack initiation) that we aim to reproduce with simulations. Although multiaxial fatigue has long been an area of active experimental investigation, only limited research has addressed measuring the number of cycles for fatigue crack nucleation and early growth within the first few grains; nevertheless, some trends are consistent and systematic. For example, Suhartono and coworkers [8] performed tension–compression and torsion (i.e., shear-dominated) tests on multiple alloys and found that the former initiated a larger number of cracks. Akiniwa et al. [9] assessed the very high cycle fatigue resistance (low applied strains) of spring steel and found that torsion specimens endured about two orders of magnitude longer lives than in tension–compression. Kandil et al. [10] evaluated the effects multiaxial loading on low cycle fatigue (high applied strains) of austenitic stainless steel under equivalent strain ranges and found that fatigue lives for tension–compression tests were shorter by a factor of five to ten than shear tests. In addition, Garud [11] analyzed the effects of multiaxial loading and compared fatigue experiments under multiple loading conditions in LCF. His approach employed a criterion based on plastic work to correlate the finding that torsion tests resulted in longer lives than the tension–compression tests by a factor of three to five.

Multiaxial fatigue has been recently revisited in terms of the assessment of crack nucleation and growth in notched specimens. Sakane et al. [12] studied tension–compression and torsion fatigue of 304 stainless steel notched bars to conclude that, under equivalent nominal stress amplitude, torsion is less damaging than axial loading; Gates and Fatemi [13] reached a similar conclusion for Al 2024-T3. Atzori et al. [14] analyzed notched specimens of C40 normalized steel under nominal load ratios of $R = -1$ and $R = 0$, and found that the lower R ratios had significantly longer fatigue lives for similar stress amplitudes. Gladskyi and Fatemi [15] studied low carbon steel and found that the notch effect was more pronounced in tension–compression loading compared to torsion, in spite of higher stress concentration factor for the latter. In addition, they observed that notches have a more detrimental effect (compared to smooth specimens) for HCF conditions (lower strain amplitudes), which was also concluded by Gao et al. [16] for 16MnR steel. This is expected, of course, from historical understanding of notch effects. However, surprisingly few data exist in the literature regarding coupled effects of multiaxial stress state and notches on growth of microstructurally small fatigue cracks.

This brief summary of experimental results highlights some general trends in fatigue crack initiation that are common across multiple material systems under equivalent nominal applied loading conditions:

(1) Shear loading and low R ratios are less damaging than axial tension–compression loading for low and high equivalent applied stresses or strains.
(2) The differences in number of cycles to failure for notches and smooth specimens is most pronounced with decreasing applied strain (i.e., higher strains reduce notch sensitivity).

The following sections will assess whether the recently developed microstructure-sensitive computational fatigue framework [1,5] for formation and early 3D growth of microstructurally small cracks can reproduce these trends.

3. Modeling and simulation

3.1. Crystal plasticity constitutive model

The elastic–plastic behavior at the grains scale depends on a deterministic, physically-based crystal plasticity constitutive model for RR1000 Ni-base superalloy, as outlined in detail elsewhere [1,5,17]. In succinct terms, the crystallographic shearing rate is given by

$$\dot{\gamma}^{(\alpha)} = \dot{\gamma}_0 \exp\left[-\left(\frac{F_0}{k_b T}\right)\left\langle 1 - \left\langle \frac{|\tau^{(\alpha)} - B^{(\alpha)}| - S^{(\alpha)}\mu/\mu_0}{\tau_0 \mu/\mu_0} \right\rangle^p \right\rangle^q\right] sgn(\tau^{(\alpha)} - B^{(\alpha)}), \tag{1}$$

where $\dot{\gamma}^{(\alpha)}$ is the shearing rate of slip system $\alpha, \tau^{(\alpha)}$ is the resolved shear stress, T is the absolute temperature, F_0, p, q, $\dot{\gamma}_0$, τ_0, μ, and μ_0 are material parameters that may differ for octahedral and cube slip systems, as listed in Table 1 for 650 °C, and k_b is Boltzmann's constant. The formulation considers 12 octahedral and 6 cube slip systems along. The model was implemented as a user-material subroutine (UMAT) in [18] using an implicit integration scheme based on the Newton–Raphson with incremental line search and backward-Euler methods. The slip resistance $S^{(\alpha)}$ serves as a threshold stress for plastic flow and the back stress $B^{(\alpha)}$ accounts for directional hardening and depend on the shear rate as follows:

$$\dot{S}^{(\alpha)} = \left[h_S - d_D(S^{(\alpha)} - S_0^{(\alpha)})\right]|\dot{\gamma}^{(\alpha)}| \tag{2}$$

$$\dot{B}^{(\alpha)} = h_B \dot{\gamma}^{(\alpha)} - r_D^{(\alpha)} B^{(\alpha)} |\dot{\gamma}^{(\alpha)}| \tag{3}$$

Here, $r_D^{(\alpha)} = \frac{h_B \mu_0}{S^{(\alpha)}} \left\{\frac{\mu_0'}{f_c \lambda} - \mu\right\}^{-1}$ and S_0, h_B, h_S, d_D, μ_0', f_c, λ, are constants that differ for octahedral and cube slip planes (see Table 1). The constitutive model was calibrated using the cyclic stress–strain experimental data from smooth specimens in Ref. [19]. Further