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Microstructure-sensitive extreme value probabilities for high cycle fatigue of Ni-base superalloy IN100

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ABSTRACT

To quantify the effects of interactions between various microstructure attributes on fatigue life in the high cycle fatigue (HCF) regime, we have proposed a new microstructure-sensitive extreme value statistical framework. This framework couples the extreme value distributions of certain fatigue indicator parameters (FIPs) or response functions to the correlated microstructure attributes that exist at the extreme value locations of these FIPs. We demonstrate the application of this statistical framework to investigate the microstructure-sensitive fatigue response of the PM Ni-base superalloy IN100 at 650 °C. To accomplish this task, we construct statistical volume elements (SVEs) used to compute the local response for 200 instantiations of IN100. These SVEs are constructed and simulated via the finite element method with crystal plasticity constitutive relations. The results of the simulations are used to explore extreme value statistics of the FIPs for these microstructures. The extreme value distributions of the Fatemi–Socie FIP are fit with high confidence by the Gumbel distribution and are defined in a representative nature with as few as 25 simulated microstructure instantiations (i.e., SVEs). The extreme value marked correlation functions of the apparent Schmid factor based on the geometry of the slip systems relative to the loading direction indicate that cube slip may be important to fatigue crack formation in this material system. This supports previous experimental observations of fatigue crack formation and microstructurally small fatigue crack growth along cube planes in IN100 in grains that are unfavorably oriented for octahedral slip at elevated temperatures.

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1. Introduction

Scatter in the high cycle fatigue (HCF) life of specimens or components depends on the extreme value probabilities of having existing hot spots or regions with increased local driving forces for fatigue damage formation (i.e., fatigue crack formation and microstructurally small crack propagation). Specifically, the probability of fatigue damage formation in a particular volume of material is established by the extreme value (i.e., rare event) probability of a particular existing combination of microstructure attributes that couple with the applied stress state such that fatigue cracks form and propagate. Coupling of microstructure attributes with loading conditions and the resulting fatigue response is the main source of both scatter and size effects in fatigue in the absence of other random environmental factors (e.g., temperature, atmosphere). As such, we commonly observe scatter in the fatigue response between multiple material volumes (or components) even when they

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are fabricated from the same batch of processed material and tested in nearly identical environments. Although environmental effects can also contribute to the probability of surface to subsurface transition of crack formation, they are not considered in this particular work. The main emphasis of this work is on developing a consistent methodology to characterize correlations of microstructure attributes that exist with high probability relative to the nominal microstructure in regions where the fatigue driving forces are maximum (i.e., extreme value).

The dependence of fatigue damage formation on various microstructure attributes has been investigated extensively; several reviews have been published on the subject (Suresh, 1998; McDowell, 1996). For example, second phase inclusions or pores, large grains that are favorably oriented for slip, or grains adjacent to grains that are unfavorably oriented for slip have each been linked to fatigue damage formation in several metallic polycrystalline material systems. Identifying the underlying microstructure attributes that drive fatigue damage formation in material systems with multiple phases, complex processing histories, etc., however, is often complicated by the fact that multiple interacting microstructure features couple with the imposed cyclic plastic deformation and stress state to increase the local driving forces for fatigue damage formation. In most cases, this dependence cannot merely be deduced from direct quantitative image analysis of various microstructure attributes. Assessment of the coupling of microstructure attributes with the driving forces for fatigue damage formation requires a combination of experiments and computational simulation, along with a connective framework based on extreme value statistics.

In general, fatigue damage formation in polycrystalline metallic materials is primarily driven by irreversible slip on the scale of the microstructure. In addition, interacting microstructure attributes (e.g., grains, phases, inclusions, and voids) can increase local slip and associated driving forces for fatigue damage at the microstructure scale. In HCF, where stress amplitudes remain below the macroscopic flow stress and cyclic plasticity is quite heterogeneous, fatigue lives are dominated by fatigue damage formation rather than by physically small or large crack propagation (cf. McDowell, 1997, 1999; Miller, 1991, 1993). Accordingly, the emphasis is placed on cyclic plasticity-based fatigue indicator parameters (FIPs) that reflect probability of microstructure scale crack formation and microstructurally small crack growth.

For most applications, large numbers of experiments are necessary to meaningfully quantify any variability in fatigue life and to identify any change in the mechanism of fatigue damage formation as a function of applied loading conditions for a given specimen size. Typically, insufficient experimental data are available to support this quantification. Moreover, the mathematical form of the tails of the probability distributions for the driving forces for fatigue damage formation, such as the local distributions of stress/strain, are not well characterized; moreover, the dependence of the character of those tails on single and/or interacting microstructure attributes are not well understood.

In this work, we are primarily concerned with how the crystallographic attributes of a polycrystalline microstructure (e.g., grain orientation, disorientation, size, and shape distributions) affect local driving forces for fatigue crack formation and early growth in HCF. In general, plastic strain inhomogeneity at the grain level in polycrystals subjected to cyclic loading is directly linked to crystallographic texture. Winter et al. (1981) observed that plasticity occurs preferentially in grains having slip systems with high Schmid factors, with slip localized within slip bands. Using crystal plasticity simulations to calculate distributions of cyclic slip in polycrystals, Bennett and McDowell (2003) demonstrated that distributions of slip could be quite heterogeneous in HCF. This heterogeneity is directly related to complex interactions between grains of differing orientations. Sauzay and Jourdan (2006) explored these types of interactions between grains by computationally characterizing the distributions of elastic stress fields around grain clusters at the free surface using elastic FE simulations. They predicted that grain interactions could affect the local resolved shear stress by as much as 18% in copper and austenitic stainless steels depending on the local orientations of the neighboring grains. Inhomogeneity of elastic stress fields corresponds to localization of plastic strain in regions of stress concentration associated with the jump of the elastic stiffness across grain boundaries and compatibility requirements of the polycrystal. Specifically, we will consider the effects of local crystallography (e.g., phase, grain orientation, grain disorientation, grain topology, etc.) on slip in a powder metallurgy (PM) Ni-base superalloy, IN100.

Ni-base superalloys are predominantly used in aircraft gas turbine engines due to their high strength and creep resistance at high temperatures that is conferred by coherent γ' Ni_3Al precipitates of $L1_2$ face-centered cubic (fcc) structure. These precipitates are dispersed in the γ austenitic Ni solid solution matrix of fcc crystal structure and provide excellent resistance to slip. Commonly, fatigue damage formation in polycrystalline superalloys has been linked to the existence of large pores or non-metallic inclusions introduced during processing. Often, inclusions debond from the matrix or crack during primary forming processes. During loading, the stress concentrations at inclusions/pores often lead to the formation of fatigue cracks (Hyzak and Bernstein, 1982; Goto and Knowles, 1998; Pang and Reed, 2003). However, as processing techniques improve, cleaner Ni-base superalloys are being developed that have lower number density of inclusions/pores; consequently, fatigue cracks are increasingly observed to form along crystallographic planes. For example, Jha et al. (2005) noted that subsurface fatigue crack formation occurs in individual grains absent of any voids/inclusions in René 88DT, particularly at lower stress amplitudes (i.e., in the HCF regime). In this case, the nucleation region associated with the size of the crystallographic facets at the sites of fatigue crack formation was observed to be much larger than the average grain size. This suggests that cracks tend to form in larger grains. In the same alloy, Shyam et al. (2004) noted that cracks form predominantly in larger grains or at inclusions near large grains. Additionally in René 88DT, Miao et al. (2007) also observed that most critical (i.e., life-limiting) fatigue cracks in the HCF/VHCF regime initiate crystallographically away from the surface. The grains in which these cracks form were observed to be large in size relative to the average grain size. Here these grains were associated with higher Schmid factors, indicating they are oriented favorably for slip. Others have shown that slip bands associated with shearing of