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Microstructure-sensitive extreme-value probabilities of high-cycle fatigue for surface vs. subsurface crack formation in duplex Ti–6Al–4V

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Abstract

The distributions of the extreme-value driving force(s) for surface vs. subsurface fatigue crack formation (nucleation and early growth) in high-cycle fatigue are evaluated for a microstructure variant of duplex Ti–6Al–4V. In polycrystalline metals, previous work has explored estimation of the driving force(s) for fatigue crack formation at the scale of the grains by computing non-local fatigue indicator parameters (FIPs) based on the cyclic plastic strain averaged over domains on the length scale of the grains. Instantiated statistical volume elements (SVEs), which sample the distributed microstructure attributes of interest for a given material system, can be simulated via the finite element method with embedded polycrystalline plasticity models to estimate the distributed plasticity and resulting FIPs. This strategy of simulating multiple SVEs is in contrast to the simulation of a single representative volume element which is typically untenably large for extreme-value distributions of microstructure attributes or response variables. In this work, multiple SVEs are instantiated with both traction-free (i.e. surface) boundary conditions and fully periodic (i.e. subsurface) boundary conditions. In addition to estimating the extreme-value distributions of the FIPs, newly introduced extreme-value marked correlation functions are applied to characterize the coupled crystallographic microstructure attributes (e.g. grain size, grain orientation, grain misorientation) that most influence the extreme-value distributions of the FIPs. It is shown that there is overlap in the distributions of the driving forces for surface vs. subsurface crack formation in the low to moderate range of failure probability based on FIPs; however, at higher failure probability levels, the driving forces are highest for surface crack formation. The overlap in the distributions of the driving forces for fatigue crack formation in the low to moderate probability range may assist in describing the competing surface vs. subsurface failure modes that are observed experimentally.
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Keywords: High-cycle fatigue; Extreme value statistics; Ti–6Al–4V; Crystal plasticity; Texture

1. Introduction

In most advanced metallic polycrystalline alloys, significant scatter is observed in the overall fatigue life. Much of this scatter is directly related to the stochasticity of microstructure, particularly in the high-cycle fatigue (HCF) regime. Marines et al. [1] observed a transition in fatigue mechanisms between 10^6 and 10^7 cycles to failure in aluminum alloys. For Al 2024-T3, life-limiting cracks in samples that exhibited fatigue lives with fewer numbers of cycles were observed to form at broken inclusions; however, in samples with longer fatigue lives, the life-limiting cracks were observed to form at persistent slip bands near the surface (see Fig. 1). The transition between the two regimes in this material system (where these competing mechanisms were observed) exhibits a much higher scatter in the overall fatigue life than either the low-cycle fatigue (LCF) or

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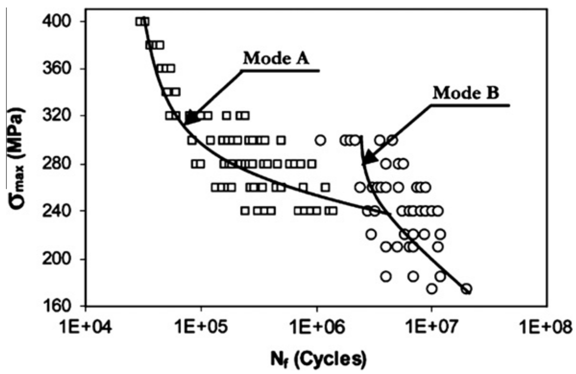

Fig. 1. S–N curve for Al 2024-T3 ($R = 0.1$), exhibiting two distinct failure modes depending on the number of cycles at failure. (Reprinted from Ref. [1], with permission from Elsevier.)

very-high-cycle fatigue (VHCF) regimes. A transition from surface to subsurface fatigue crack initiation between 10^6 and 10^9 cycles has also been observed in titanium alloys [2]. Ravi Chandran and Jha [3] reported that two competing mechanisms of fatigue damage formation were observed in Ti–10V–2Fe–3Al. The probability of fatigue failure was shown to relate to the probability of clusters of primary α grains existing at the surface. Shorter lives were observed if these primary α-grain clusters existed at the specimen surface than if they existed in the subsurface. Monte-Carlo simulations based on Poisson defect statistics supported these observations. In addition, Szczepanski et al. [4] observed a dramatic increase in the overall scatter in fatigue life as lives increased from LCF to VHCF in Ti-6246, as shown in Fig. 2. Although surface fatigue crack formation appears to be the primary failure mode at higher stress amplitudes for a given R ratio, there is increasing competition between surface and subsurface fatigue crack formation as the stress amplitude decreases.

In Ti–6Al–4V, fatigue crack formation is primarily crystallographic and is highly influenced by grain orientation.

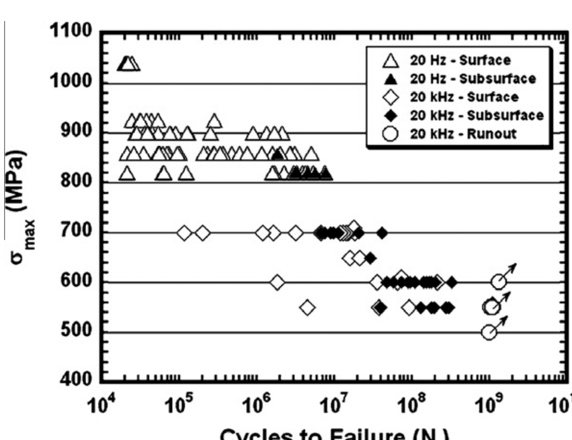

Fig. 2. The fatigue variability of Ti-6246 characterized from repeated testing at several stress magnitudes from HCF to VHCF showing mean vs. life-limiting behavior. (Reprinted from Ref. [4], with permission from Springer.)

Several studies have observed that the life-limiting fatigue cracks nucleated on basal planes. For example, Bridier et al. [5,6] investigated fatigue crack formation in Ti–6Al–4V in both LCF and HCF, respectively, and observed that cracks formed mostly on basal slip planes and less frequently on prismatic slip planes. Specifically, the basal and prismatic planes on which the life-limiting cracks formed exhibited high Schmid factors; moreover, a bias was observed towards primary α grains with orientation of applied stress closer towards the c-axis, indicating a preference for the formation of cracks on planes with somewhat higher peak tensile stress normal to the basal (or prismatic) plane. Gilbert and Piehler [7] observed preferential subsurface fatigue crack formation in Ti–6Al–4V in clusters of primary α grains oriented favorably for slip on pyramidal $\langle a + c\rangle$ planes and primary α grains oriented favorably for basal slip.

Fatigue failure is governed by the tails (i.e. extreme-value regions) of joint probability distributions of attributes (e.g. grain size) and responses (e.g. fatigue indicator parameters (FIPs)). For example, if the fatigue response of a particular material is controlled by the largest inclusion of a certain type, an understanding of the distribution of inclusion sizes in the critically stressed regions is essential to modeling the fatigue life for that particular material. Additional scatter can also be attributed to competing mechanisms that change depending upon the applied stress amplitude and stress state. This is the case in the previously cited example, which demonstrated competition between surface- and subsurface-dominated fatigue failure modes based on the probability of certain existing microstructure attributes (i.e. the existence of clusters of primary α grains) [3]. The main focus of the present work is to understand the influence of the free surface on the competing extreme-value distributions of response in Ti–6Al–4V under HCF or VHCF conditions as a function of applied stress amplitude.

Classical statistical treatments of fatigue variability have been based primarily on large numbers of experiments as necessary to obtain a statistically significant sample. Designers then use these data to predict component life with an acceptable level of risk. Such data collection requires significant time and resources and does not necessarily provide understanding of the mechanism(s) that most influence the variability of fatigue life. In addition, the resulting predictions often change with varying sample sizes. A widely used function for probability of failure in fracture and fatigue, established by Weibull [8], relies on fitting parameters to experimental data and does not explicitly link variations in the microstructure to variations in component life.

More recent microstructure-sensitive probabilistic models have been developed which potentially offer improved description of the variability of fatigue response; they are based on the underlying distributions of microstructure attributes relevant to the processes of fatigue crack formation. Existing probabilistic methods that use single variate