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A new paradigm of fatigue variability behavior and implications for life prediction

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Abstract

The treatment of the fatigue variability behavior has traditionally been based on the understanding of the mean-lifetime behavior. With reference to two turbine engine materials, an $\alpha + \beta$ titanium alloy and a nickel-based superalloy, it is shown that the traditional approach may not accurately describe the fatigue variability behavior of these materials. Decreases in stress level, or microstructural change directed at increasing the mean lifetime, were found to affect mean and worst-case (life-limiting) fatigue behavior differently, and these differences could not be accounted for in the traditional understanding. In particular, the life-limiting mechanism was controlled by crack growth although the mean-lifetime response was increasingly dominated by crack initiation with decreasing stress level. A new paradigm of fatigue variability was therefore suggested, in which the total uncertainty in lifetime breaks down into the variability in (1) the worst-case mechanism and that in (2) the classical, mean-lifetime governing response. The effects of microstructure and temperature on the fatigue variability behavior were studied with respect to the new paradigm and found to have a very systematic effect on the worst-case and the mean behavior, depending on the degree of influence of these variables on the crack initiation and the growth regime.

Keywords: Fatigue variability; $\alpha + \beta$ titanium alloy; Nickel-base superalloy; Life-limiting behavior; Microstructure; Probability of failure

1. Introduction

Fatigue lifetime variability behavior is generally described in terms of variability about the overall mean behavior [1–3]. The life prediction approach of fracture critical turbine engine components has also been governed by the conventional understanding of fatigue variability [4,5]. The minimum book life, or the limiting-lifetime, is taken as the extrapolation of the variability about the overall mean behavior at some given set of conditions corresponding to a predetermined probability of failure (POF), typically taken as 1 in 1000 [4]. As a result, there is large degree of uncertainty associated with the limiting-lifetime prediction and it is estimated that a significant number of components may be discarded while still possessing a considerable fraction of their useful life [5]. A more accurate predicted life may require a re-evaluation of the traditional approach to fatigue variability, especially with respect to its applicability to life prediction.

In this paper, the fatigue variability behavior of two common turbine engine materials is discussed. These were: the $\alpha + \beta$ titanium alloy, Ti–6Al–2Sn–4Zr–6Mo (Ti-6-2-4-6) and a powder metallurgy (P/M) processed nickel-based superalloy. There are few studies of fatigue variability of titanium alloys, although their mean fatigue behavior has been widely studied, and correlations between microstructure and loading variables versus the mean behavior have been established in many cases [6–9]. In $\alpha + \beta$ titanium alloys, depending on the microstructure, the mean lifetime has been related to the equiaxed α size, and lamellar α/β colony size [7–9]. Decreasing the controlling microstructural unit is known to increase the mean lifetime [9], especially at lower stress levels. It is also well known in titanium alloys that, crack initiation has increased contribution to the total lifetime as the stress level is decreased [10,11]. The relationship of these variables to the fatigue lifetime-variability, however, has not been widely addressed.

The fatigue behavior of P/M nickel-based superalloys has also been reported in many studies [3,12–18]. These materials

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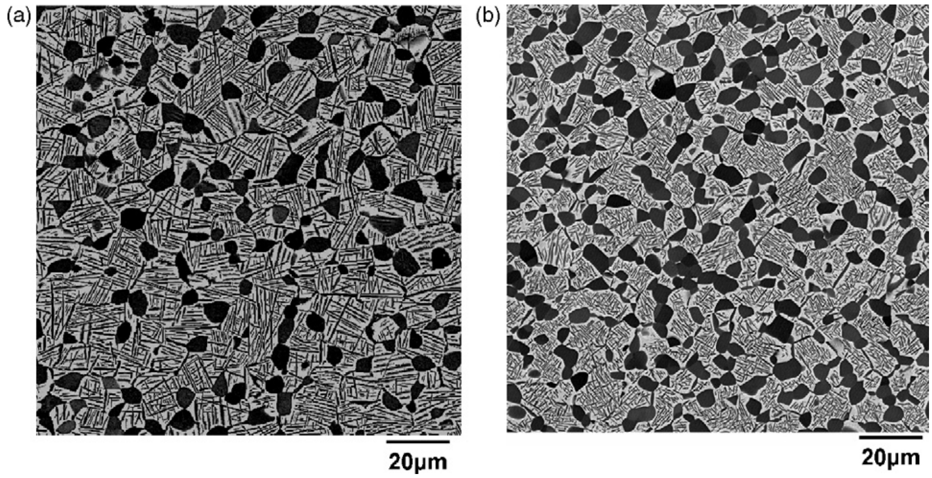

Fig. 1. Microstructures of the Ti-6-2-4-6 alloy: (a) the pancake microstructure and (b) the disk microstructure.

are known to fail from crystallographic crack initiation [17,18], as well as processing related constituent particles [17–20] and voids [12,13,15,16]. The treatment of fatigue variability behavior of these materials has been largely focused at obtaining the lifetime distribution from variation in the given microstructural feature as well as, in some cases, the variation in the crack initiation and crack growth rates about the mean response [3,14–16]. From a design-life perspective, a more important problem may be the competition between mechanisms and their ranking in terms of likelihood of occurrence, as addressed in some studies [21,22].

Recently, it was shown that, the competition between mechanisms, and the interplay between the number density of relevant microstructural features and the specimen volume, can produce a duality in the S–N fatigue behavior [23]. In a different material [24], the competition, and the sequence of occurrence of mechanisms, was shown to produce a superposition of variability in two mechanisms at the same stress level. These and other studies [25] point to growing evidence that the fatigue variability behavior may not follow the same trend as the mean response. It is crucial to capture and incorporate these fatigue variability responses for reliable life prediction, as it appears this behavior cannot be accounted for in the traditional, mean-based framework.

2. Materials and experimental procedure

The materials in this study were an $\alpha + \beta$ titanium alloy, Ti-6-2-4-6 and a P/M processed nickel-based superalloy. Two heats of the Ti-6-2-4-6 alloy with constant composition but different optical microstructures were considered. These were designated as the pancake and the disk microstructure and are shown in Fig. 1(a) and (b), respectively. As shown, both microstructures had a duplex structure with equiaxed primary α (α_p) grains in a transformed β matrix. These however, differed significantly in terms of their crystallographic texture as shown in Fig. 2.

The microstructure of the nickel-based superalloy is shown in Fig. 3. The γ-primary γ' structure is revealed in Fig. 3(a) and the secondary γ' morphology is shown in Fig. 3(b). Since the tertiary γ' precipitates were very fine, they are not resolved at this magnification. The median γ grain size was about 4 μm.

Fatigue specimens were electro-discharge machined in the circumferential orientation from the forgings of the two heats

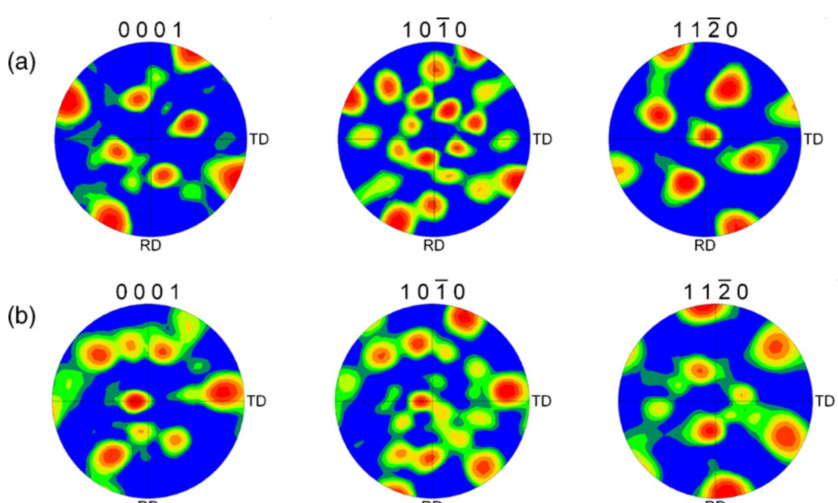

Fig. 2. Crystallographic texture of the two microstructures: (a) pancake and (b) disk.