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Deformation heterogeneities and their role in life-limiting fatigue failures in a two-phase titanium alloy

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Abstract—Fatigue crack-initiation sites in Ti–6Al–2Sn–4Zr–6Mo (Ti–6–2–4–6), an $\alpha + \beta$ titanium alloy used in turbine engine applications, were characterized with emphasis on distinguishing the microstructural neighborhoods and mechanisms that produce the life-limiting failures vs. those that promote the mean-lifetime behavior. The characterization methods included quantitative tilt fractography, focused ion beam milling across crack-initiation facets, and electron backscattered diffraction analysis. The motivation for discerning between the life-limiting and the mean-dominating crack-initiation microstructural neighborhoods stemmed from the previously developed understanding that the mean and the life-limiting behaviors respond differently to stress level (and many other variables), leading to an increasing separation between the two subpopulations as the stress level is decreased, thereby increasing the variability in lifetime. The different rates of response of the two behaviors was found to arise because the life-limiting mechanism was dominated by the crack-growth lifetime, with microstructural-scale crack-initiation occurring within the first few fatigue cycles, whereas the mean behavior was increasingly dominated by the crack-initiation lifetime as the stress level was decreased. Representative specimens for 2-D characterization of crack-initiation neighborhoods were selected from life-limiting and mean-dominating populations generated by fatigue tests on a duplex $\alpha + \beta$ phase microstructure of Ti–6–2–4–6 under a narrow range of applied stress amplitudes. A compilation of data on the crack-initiation facet and the neighborhood of the faceted grain from multiple specimens pointed to at least four categories of critical microstructural configurations, each representing a set of necessary (but perhaps not sufficient) conditions for crack-initiation in this alloy. Based on this characterization, a hypothesis for the life-limiting fatigue behavior is presented. The hypothesis invokes the concept of hierarchy of fatigue deformation heterogeneities, which is suggested to develop within the first few fatigue cycles. The deformation heterogeneity is suggested to be linked to the underlying randomness and hierarchy in the microstructural arrangements. This hypothesis appears to explain the occurrence of crack-growth-lifetime-dominated, life-limiting failures in the regime of high-cycle fatigue, as shown in this study, and suggests a probability of occurrence of such failures even in the very-high-cycle fatigue regime, although with diminishing probability as the stress level is decreased.

Keywords: Hierarchy of deformation heterogeneities; Life-limiting mechanism; Fatigue life; Crack-initiation neighborhood; Ti–6Al–2Sn–4Zr–6Mo

1. Introduction

1.1. Non-uniqueness of fatigue crack-initiation mechanisms

While fatigue crack-initiation in metallic materials is known to occur by cyclic damage accumulation at the microstructural scale [1], where the underlying deformation mode is often dislocation slip, the mechanisms in terms of the process of crack formation and the role of the surrounding microstructure are diverse, and strongly dependent on the alloy composition, microstructure and loading condition. In terms of the process of formation of a crack and the involvement of neighboring microstructural phases, it is not uncommon to find differences among different studies on the same alloy (e.g. [2–4]). This is not surprising, given that the specific characteristics of a mechanism are strongly tied to the details of the microstructure and the loading variables. It is also reasonable that the understanding of the mechanisms will in some cases periodically evolve with the introduction of new characterization and modeling tools. However, as has been suggested in several studies [5–15], the diversity of mechanisms could also be related to the non-uniqueness of crack-initiation mechanisms, even for the same alloy, microstructure and loading conditions. For example, in Refs. [5–9], the fatigue lifetime distributions in Ti–6Al–2Sn–4Zr–6Mo were shown to be a superposition of at least two separate distributions, which were attributed to different mechanisms in terms of microstructural arrangements and the process of crack formation, occurring in the same microstructure and at the same stress level. These studies also demonstrated that

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the two superimposing distributions respond differently to variables such as microstructure and temperature, thereby affecting the separation between the two [5–9] with respect to these variables. A separation of lifetimes due to multiple mechanisms was also reported in IN100, a Ni-base superalloy [10], although the associated crack-initiation modes were different from crystallographic facet formation commonly seen in titanium alloys. Similarly, in Ref. [11], multiple mechanisms, in terms of crack-initiating microstructural configuration, were characterized in Ti–6Al–4V that produced a separation in lifetimes. Refs. [12,13] provide a discussion of competing fatigue modes in Ti–10V–2Fe–3Al, a β titanium alloy. Similar competing mode behavior was shown in Ni-base superalloys in Refs. [12,14] and in steel in Refs. [12,15]. The existence of multiple mechanisms was also demonstrated by probabilistic simulations using fatigue indicator parameters as a metric for fatigue deformation [16]. Given the multiplicity of possible mechanisms, as discussed above, an important question from a life-prediction perspective is whether an observed crack-initiation mechanism pertains to the mean fatigue behavior or to the minimum, life-limiting behavior. This question is especially significant because the life-limiting mechanisms, which are likely due to the interaction of extreme microstructural neighborhoods with the applied loading, may often occur rarely, and thus be difficult and expensive to capture via experimental or empirical methods, which suggests the need for a more physical basis of predicting such failures. In the following, the mechanisms specific to titanium alloys are elucidated. Before further discussion, it is useful to emphasize that in this paper "mechanism" refers to the process of formation of the crack-initiation site and the role of the microstructural neighborhood in that process, and not the underlying mode of deformation under fatigue.

With respect to the titanium alloys, the factors discussed above appear to be further accentuated due to the wide range of compositions and the complexity of the associated microstructures in terms of morphology and arrangement of phases, crystallographic relationships, and existence of multiple length scales [17]. The intricacy of the microstructure and crystallography manifests itself in the mechanisms of accommodation of plastic deformation. Titanium alloys offer a number of slip systems, but also exhibit strong slip anisotropy. The slip systems include slip along the ⟨a⟩ or $\langle 11\bar{2}0\rangle$ directions on basal, prismatic and pyramidal planes, and ⟨c + a⟩ slip on first-order and second-order pyramidal planes [18,19]. Each of these slip modes has a different slip strength, and while the relative difference in strengths varies with the alloy, basal ⟨a⟩ and prismatic ⟨a⟩ systems have lower critical resolved shear stress (CRSS) than the pyramidal ⟨a⟩ and ⟨c + a⟩ systems [17–19]. Maintenance of compatibility of deformation requires slip by hard, off-basal slip systems and/or twinning [19]. Additionally, the Burgers crystallographic relationship between the hexagonal close-packed (hcp) α phase and the body-centered cubic (bcc) β phase allows only one of the three ⟨a⟩ directions in α to be in close alignment with the ⟨110⟩ slip direction in β which results in significant anisotropy in deformation across α/β interfaces [20]. From the perspective of fatigue crack-initiation, the anisotropy of deformation can provide avenues for plastic strain concentration within contiguous slip bands, coupled with strain incompatibilities at certain interfaces, leading to stress concentration at those locations. In addition to slip, twinning is an important mode by which plastic deformation is accommodated in titanium alloys, although this mode is not seen in alloys with high aluminum content [19], which is the case in the present study.

While there are some common features of crack-initiation across different titanium alloys, as reports in the literature undoubtedly reveal [2–4,21–27], the specifics of the mechanisms, particularly the characteristics and the process of formation of the crack-initiation site, varies among studies on similar alloys and microstructures under similar type of fatigue loading. One interpretation of this can be that the crack-initiation process is highly sensitive to minor differences in compositions and microstructure. However, given the various paths for deformation accumulation and strain incompatibility, it seems reasonable that a unique crack-initiation process may not exist in these alloys.

Most studies of fatigue crack-initiation in duplex microstructures of α + β to near-β titanium alloys (which are of interest in this paper) have shown that crack-initiation is accompanied by facet formation across primary-α (α_p) particles [2–4,21–27]. Furthermore, several researchers have shown that faceting of α_p is favored in microtextured regions that are suitably oriented for either basal ⟨a⟩ or prismatic ⟨a⟩ slip [2,25]. Facets have been shown to form uniformly across the microtextured region in some studies [2], but have also been observed to be concentrated in a smaller area within an otherwise much larger microtextured region [8]. An example of the former is seen in Bridier et al.'s [2] study on α/β-forged Ti–6Al–4V (Ti–6–4) with a duplex microstructure. The fatigue experiments in their study were performed under strain control, and the loading regime was reported to be mostly elastic on a bulk scale after the first two cycles. The lifetime under those loading conditions, which can be considered to be in the low-cycle fatigue (LCF) regime, was on the order of 20,000 cycles. An example of the latter result can be found in a study by Szczepanski et al. [8] on Ti–6Al–2Sn–4Zr–6Mo (Ti–6–2–4–6), another α + β alloy, in the duplex microstructural condition. The loading regime in that study was also nominally elastic, but in the very-high-cycle fatigue (VHCF) range, where lifetimes were of the order of 10^8–10^9 cycles.

The crack-initiation facet plane is found to be the basal or close-to-basal plane in a majority of the studies (e.g. [2–4,7,8]), although facets along the prismatic planes have also been observed [2]. Some researchers have ascribed the facet plane to be a cleavage plane that is inclined to the basal plane. For example, Neal and Blenkinsop [21] in their study on two α + β alloys, IMI 550 and Ti–6–4, in a duplex microstructural condition suggested that the facet plane corresponded to the $\{10\bar{1}7\}$ cleavage plane. The loading regime in their study was nominally high-cycle fatigue (HCF), where the lifetimes were reported to be of the order of 10^6 cycles.

In terms of the process of formation of crack-initiation facets, a range of mechanisms has been proposed. These mechanisms span from (i) quasi-cleavage where the facet plane is normal to the loading axis (e.g. Ti–6–4 with duplex microstructure[3]); (ii) a combination of basal slip and normal stress across the basal plane leading to facets whose normals are inclined <45° to the loading axis (e.g. Ti–6–4 with duplex microstructure in the LCF loading regime [2], and Ti–6–4 with fully lamellar microstructure in the HCF regime [4]); and (iii) pure slip where the facet plane is close to 45° to the loading axis (e.g. Ti–6–4 with a fully lamellar microstructure in the HCF loading regime [4]). In addition