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Activation of life-limiting fatigue damage mechanisms in Ti–6Al–2Sn–4Zr–6Mo

Alisha L. Hutson [b,*], Sushant K. Jha [c], William J. Porter [b], James M. Larsen [a]

[a] US Air Force Research Laboratory, Materials and Manufacturing Directorate, AFRL/RXCM, Wright-Patterson Air Force Base, OH 45433, USA
[b] University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0020, USA
[c] Universal Technology Corporation, 1270 N. Fairfield Road, Dayton, OH 45432, USA

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ABSTRACT

The experimental conditions that produce bimodally-distributed fatigue populations were investigated in Ti–6Al–2Sn–4Zr–6Mo, with the aim of identifying conditions favorable for characterizing life-limiting fatigue behavior. In general, the more aggressive test conditions in this effort were identified as more favorable for producing bimodally-distributed lifetime populations in which the shorter life populations were dominated by the life-limiting behavior. Data sets obtained using electropolished specimens generally exhibited bimodal distributions, and this surface condition was determined to be most suitable for investigating life-limiting fatigue behavior for a wider range of test conditions, due to the elimination of machining-induced residual stresses. It was also determined that the presence of bimodally distributed data populations, and the relative sampling of the corresponding damage mechanisms, can have a significant effect on life predictions, if the bimodal behavior is not explicitly included.

1. Introduction

The modeling of fatigue variability behavior in the metals used in turbine engine components has often been assumed to exhibit log-normally distributed variability about an experimentally determined mean fatigue life dependent on the applied loading and environmental conditions [1,2]. Recently, however, fatigue characterization of some of these materials has indicated that a single log-normal distribution about a statistical mean may not accurately represent the actual distribution of fatigue lives [3,4]. Rather, the variability in fatigue response at a given stress level often tends to separate into bimodal distributions representing minimum behavior and a mean-life dominated behavior, termed Type I and Type II behavior, respectively. Thus, the probably density representing a material's safe-life fatigue capability, depicted in Fig. 1, was often composed of two underlying probability densities, as shown schematically in Fig. 2. This separation in fatigue lifetimes, known as bimodal or competing-modes fatigue, has been observed in a wide range of alloys, including nickel-base superalloys [5–15] the single crystal alloys [16], the titanium alloys Ti–10V–2Fe–3Al [7,17,18], Ti–6Al–2Sn–4Zr–6Mo [19–27], Ti–6Al–4V [28–32], gamma titanium aluminides [33,34], the aluminum alloy 7075-T651 [35], and others. Although such a separation of fatigue response has been known for some time [36], the significance of this behavior has not yet been generally captured in the strategies for fatigue design of turbine engine materials.

When such bimodal populations are treated together and a B0.1 (1 in 1000 probability of failure) minimum fatigue life is extrapolated, the results appear to be an overly conservative estimate of the worst-case fatigue behavior in some cases, with the extrapolated values often falling below a fatigue life prediction based solely on a crack-growth dominated mechanism [24,37]. Alternatively, situations may occur wherein the inherent life-limiting behavior is not captured in the data population, and an extrapolation of the distribution to a B0.1 lifetime may produce an overestimate of the lifetime limit [8]. Treating the populations separately, and estimating the B0.1 life based on the Type I (minimum behavior) population appears to produce a more accurate estimate of the life-limiting behavior, reduce uncertainty, and provide for improved prediction of the potential remaining life of existing components.

While bimodal behavior of fatigue lifetimes has been observed for many different alloys, it has not been observed for all experimental conditions. Thus, questions arise regarding the conditions that produce bimodal behavior and the implications for accurate life prediction if a bimodal data distribution is not observed. As indicated above, if no bimodal distribution is observed, it is possible that only the Type II damage mechanism was sampled.

* Corresponding author. Tel.: +1 937 255 2708; fax: +1 937 255 1362.
E-mail address: Alisha.hutson.ctr@us.af.mil (A.L. Hutson).

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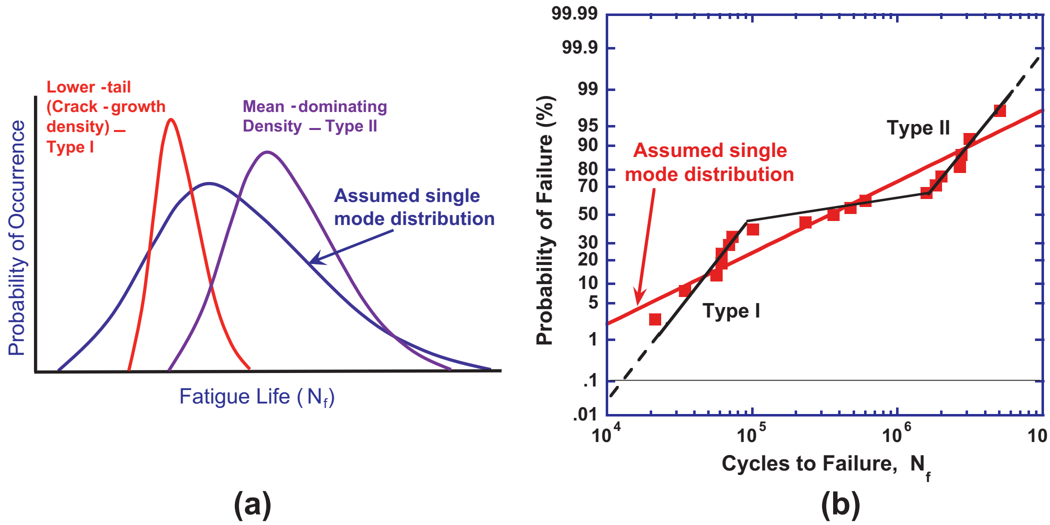

Fig. 1. (a) Schematic of single vs. bimodal data distributions [24], and (b) representative probability of failure schematic indicating B0.1 (1 in 1000) estimates with and without consideration of the bimodal nature of the data distribution.

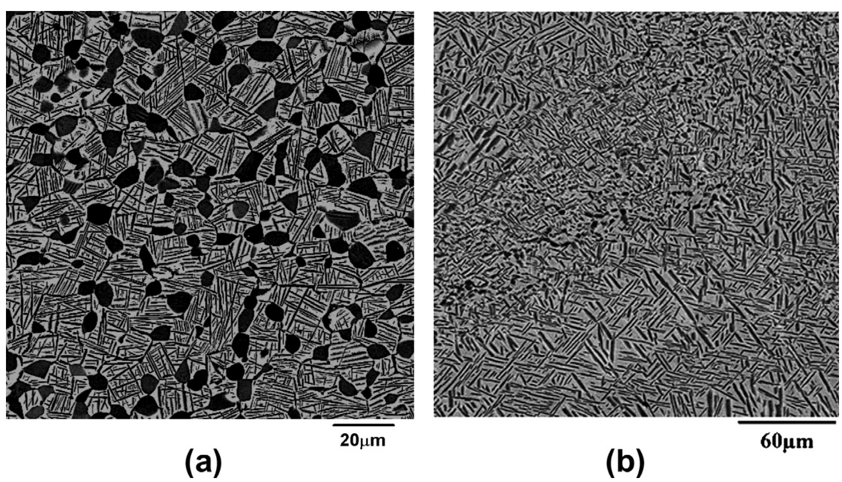

Fig. 2. Representative micrographs of (a) $\alpha+\beta$ processed and (b) through-β-transus Ti-6246.

However, with a limited number of tests, the absence of Type I behavior does not preclude the occurrence of Type I mechanisms when considering component and fleet-scale volumes of material. This study examines test conditions necessary for activation of the Type I damage mechanisms, and discusses how targeted test conditions can be used to increase the likelihood of capturing the worst-case fatigue behavior.

2. Experimental approach

Two Ti–6Al–2Sn–4Zr–6Mo (Ti6246) microstructures were studied for this effort. The first (Fig. 2a) was produced by $\alpha+\beta$ processing, and consisted of ~30% equiaxed primary alpha phase particles, with the balance being platelet shaped secondary alpha phase in a retained β-phase matrix. The second microstructure (Fig. 2b) was a Widmanstätten structure obtained by forging through the β-phase transus temperature to obtain a fully transformed microstructure that was generally absent regions of continuous primary alpha. This second microstructure, referred to as through-β-transus, was composed of fine secondary alpha platelets in a retained β matrix, with any continuous primary alpha, which typically nucleated along prior β colony boundaries, broken into a relatively fine necklace structure [38]. The $\alpha+\beta$ microstructure generally exhibited higher strength properties than the through-β-transus material, with the primary alpha particles having been shown to serve as the dominant crack initiation sites [37]. The through-β-transus material, while having slightly lower strengths, appears to exhibit improved resistance to fatigue crack propagation (FCP), enabling the use of larger critical crack sizes in component maintenance plans.

Both materials were received in their respective as-forged conditions. From these forgings, round dog-bone fatigue and compact-type, C(T), samples ~20 mm wide by ~6 mm thick were fabricated using electro-discharge machining (EDM) methods, in the circumferential and the C–R orientations, respectively. Note that the "C–R" orientation for C(T) specimens refers to loading in the circumferential direction and crack propagation in the radial direction of a pancake forging [39]. The dog-bone specimens were machined to have a uniform gage section, nominally 12.5 mm long by 4 mm in diameter. Low-stress grinding (LSG) was used to obtain a machined-sample finish of RMS 8 micro-inches (~200 μm) for both geometries. Dog-bone specimens tested with this finish are referred to as "LSG" samples. Some of the dog-bone specimens were