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The effects of microstructure and porosity on the competing fatigue failure mechanisms in powder metallurgy Ti-6Al-4V

Matthew K. Dunstan[a], James D. Paramore[a,b], Z. Zak Fang[a,*]

[a] Department of Metallurgical Engineering, The University of Utah, 135 South 1460 East Room 412, Salt Lake City, UT 84112, USA
[b] Lightweight and Specialty Metals Branch, United States Army Research Laboratory, 4600 Deer Creek Loop RDRL-WMM-F Aberdeen Proving Ground, MD 21005, USA

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ABSTRACT

In near-net-shape manufacturing methods, such as powder metallurgy, additive manufacturing, and metal injection molding, porosity has historically been viewed as the sole limiting factor for fatigue life. This is because pores tend to act as stress concentrators. However, in this work, a fractographic analysis of Ti-6Al-4V produced through several powder metallurgy techniques has shown that microstructural faceting due to slip can cause fatigue failure, even in the presence of porosity. The likelihood of pore related failure was found to be dependent on microstructure size and morphology. Additionally, a minimum pore size threshold was found to exist for each microstructure, under which pores will not cause fatigue failure. A simple model was developed to determine this threshold based on the microstructural characteristics of the material. This model was then compared to experimental data and properly predicted the fatigue failure mechanism in over 99% of the samples examined.

1. Introduction

It has been estimated that fatigue is associated with 90% of all mechanical failures in structural materials [1]. In particular, in high cycle fatigue (HCF) and very high cycle fatigue (VHCF), crack initiation can account for over 90% of the total fatigue life [2,3]. Therefore, it is imperative to understand the mechanisms of fatigue crack initiation to better predict the overall performance of a material. In metals, initiation can be divided into three broad causes: the material's microstructural features (e.g. grain size, grain morphology, and phase compositions), porosity or inclusions, and surface defects (not including surface pores or inclusions) [4]. In a defect-free material, initiation will occur from a microstructural weak point, such as persistent slip bands that form a notch at a free surface [5,6], grain boundaries [7–9], or slip systems [10,11]. In materials with defects such as pores, inclusions, or surface defects, the conventional wisdom has been that initiation will occur from these sites as they act as stress concentrators [12,13]. However, previously published works have observed an exception to this predominant thought by showing initiation to occur at microstructural features even in the presence of pores. Specifically, Zhang et al. [14] have shown for the aluminum alloy A356 that as the secondary dendrite arm spacing decreases the propensity for microstructure initiation increases. Additionally, Lados et al. [15] have reported little difference in the fatigue properties of Sr-modified A356 with a maximum pore size of 25 μm and pore free samples. A similar pore threshold has been observed by Rutz et al. for ferrous powder metallurgy alloys [16].

In order to better understand and predict the fatigue performance of pore-containing material, there is a need to know when pores begin to control failure. Determining such failure mechanisms is of particular interest for powder metallurgy (PM), additive manufacturing (AM), and casting. This is because internal defects, such as pores and inclusions, are likely to exist in materials made via these processes.

Previous research has focused on developing models that can be used to predict the fatigue life of materials based on fatigue crack initiation. However, these models only incorporate material parameters such as grain size [17–20], pre-existing cracks [20], or inclusions [21]. Poisson statistics [22–25] and finite element analysis methods [26] have also been used to determine the probability that initiation will occur at inclusions. However, as with other work, these methods have not shown to provide a model that predicts which of the aforementioned features will act as the preferential failure mechanism.

Kitagawa-Takahashi [27] diagrams have been used to determine threshold values for pre-existing cracks. An equation for this threshold was derived by Haddad et al. [28], but it only considers cracks assumed to be infinitely sharp at the crack tip. Chan [4] has further modified this threshold equation to account for pores, by introducing a stress concentration factor. However, determining the stress concentration factor

* Corresponding author.
E-mail addresses: matt.dunstan@utah.edu (M.K. Dunstan), james.d.paramore.ctr@mail.mil (J.D. Paramore), zak.fang@utah.edu (Z.Z. Fang).

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Table 1
Sample designations with microstructural type and processing conditions listed.

Designation	Microstructure Type	Processing Conditions
HSPT	UFG lamellar	HSPT as-sintered
HSPT + PC	Globular with small lamellar regions	HSPT sintered with GIF or HIP for pore closure
HSPT + PC + Bimodal	Bimodal, globular α grains in an UFG lamellar matrix	HSPT sintered with GIF or HIP for pore closure and bimodal heat treatment
HSPT + PC + Globular	Fully globular	HSPT sintered with GIF or HIP for pore closure and globular heat treatment
HSPT + PC + β-anneal	Coarse lamellar	HSPT sintered with GIF or HIP for pore closure and β-anneal heat treatment
VAC	Coarse lamellar	Vacuum as-sintered
VAC + PC	Coarse lamellar	Vacuum sintered with GIF or HIP for pore closure

of a pore is difficult, as pores can be irregular in shape. Therefore, there is still a need to develop a method for predicting this threshold value that utilizes easy to obtain material parameters.

In the current work, a study has been performed on fatigue failure initiation sites in Ti-6Al-4V samples made using powder metallurgical techniques, including both traditional vacuum sintering and the Hydrogen Sintering and Phase Transformation (HSPT) process. HSPT is a recently developed process for producing titanium alloys with an ultrafine-grained (UFG) lamellar microstructure by taking advantage of unique phase transformations in the (Ti alloy)-H systems [29–34]. In this process, titanium hydride (TiH_2) powders are used rather than elemental titanium powders, which greatly reduces interstitial contamination and improves densification [35,36]. The powder compacts are sintered in a dynamically controlled hydrogen atmosphere, which allows for microstructural manipulation. Additionally, the UFG as-sintered alloys can be heat treated without mechanical working to produce a range of wrought-like globular, bimodal, and lamellar microstructures. This results in Ti-6Al-4V with tunable properties, including tensile strengths over 1000 MPa, elongation over 20%EL, and fatigue strengths at 10^7 cycles of ~600 MPa [37,38]. Traditionally, producing such properties in PM Ti-6Al-4V requires either using prohibitively expensive pre-alloyed powders and pressure-assisted sintering techniques, or incorporating mechanical working after sintering to break up the microstructure and drive recrystallization, which would sacrifice the near-net-shape capability of PM [39].

Before HSPT's discovery, vacuum sintering of titanium and/or TiH_2 powders was typical. However, vacuum sintering produces a coarse lamellar microstructure, which can result in poor mechanical properties, particularly fatigue performance [40–43]. Specifically, HSPT processed Ti-6Al-4V has been shown to have fatigue strengths double that of vacuumed sintered Ti-6Al-4V [37].

While the bulk of the research on the mechanical properties of HSPT Ti-6Al-4V has focused on determining baseline tensile and fatigue properties [37,38,44], work has also been done to characterize the effects of porosity on fatigue properties [45,46]. Pore and microstructure controlled failure have previously been observed in HSPT Ti-6Al-4V [44,46]. However, these works have not addressed the question of when pores start to dominate fatigue failure, nor have they addressed the effects of grain size on fatigue failure mechanisms.

In the first part of this work, a fractographic analysis was conducted on Ti-6Al-4V samples produced by both traditional vacuum sintering and the HSPT process. From this work, the type of failure at the initiation site was shown to be dependent on the size and morphology of the microstructure. To quantify these observations, the second part of this work developed a simple theoretical model for predicting the effect pores will have on the fatigue life of metal alloys. This model uses readily obtainable material properties to identify a pore diameter threshold value, below which pores can be assumed to have a negligible effect on fatigue life. The model was tested against the experimental data from the fractographic analysis of the various Ti-6Al-4V microstructures. However, this model should apply to any metal alloy for which the threshold stress intensity factor (ΔK_{th}) and fatigue endurance limit (σ_e) have been obtained.

2. Materials and methods

For this study, Ti-6Al-4V samples were produced by compacting a mixture of TiH_2 and master alloy (60 wt% Al and 40 wt%V) powders with particles sizes less than 37 μm and 44 μm, respectively, to create a final composition of 90 wt% Ti, 6 wt% Al, and 4 wt%V after sintering. To vary the microstructure, a combination of sintering, heat treating, and pore closure techniques were used. Vacuum sintering was used to produce a coarse lamellae microstructure, whereas HSPT processing was used to create an UFG lamellar microstructure. Further heat treatments of HSPT-processed Ti-6Al-4V produced bimodal, globular, and lamellar microstructures. Additional details on HSPT processing methods can be found in the literature [37,47].

In an attempt to examine the fatigue properties of pore-free Ti-6Al-4V, pore closure methods were used to make fully dense samples (> 99.9% theoretical density). Due to equipment availability, it was necessary to use two types of pore closure methods. Hot isostatic pressing (HIP) was used on samples meant for fatigue crack growth testing, whereas gaseous isostatic forging (GIF) was used on the fatigue samples. HIP was performed at the United States Army Research Laboratory at 950 °C, 207 MPa, and a dwell time of one hour. GIF was performed by AMETEK Specialty Metal Products with a preheat temperature of approximately 850 °C. GIF is an alternative to HIP that utilizes high temperatures and pressures to close residual pores and voids in materials. However, the pressurization rates used during GIF are much faster than HIP. Additional details on GIF processing can be found in the literature [48,49].

Despite the different temperatures used for GIF versus HIP, all FCG specimens used in this study were heat treated above 950 °C following HIP. Therefore, the microstructure and material properties of the samples processed via GIF and HIP are identical. Designations for the various sample conditions are given in Table 1 along with the microstructure type and processing condition descriptions. Condition designations with the letters PC (pore closure) indicate either GIF or HIP was used to close porosity.

After sintering, heat treating, and pore closure processing, samples were machined into specimens for fatigue testing or fatigue crack growth tests. For fatigue tests, specimens were machined into cylindrical fatigue bars with a minimum diameter of 6.35 mm and a grip diameter of 12.7 mm. For fatigue crack growth tests, compact tension (C(T)) specimens with a thickness (B) of 4 mm and a width (W) of 36 mm were used. All fatigue and fatigue crack growth tests were conducted in air, at room temperature, at a stress ratio (R) of 0.1, and at a frequency of 35 Hz. Fatigue testing was done according to ASTM E466 [50]. Fatigue crack growth testing was done using the compliance method according to ASTM E647 [51].

Fatigue tests were conducted to understand the overall fatigue properties of the various conditions, including the endurance limit ($\Delta\sigma_e$), whereas fatigue crack growth tests were used to determine the threshold stress intensity factor (ΔK_{th}). For this work, the endurance limit is defined as the minimum stress peak-to-peak amplitude (i.e. $0.9\sigma_{max}$) corresponding to a fatigue life of 10^7 cycles. Fatigue crack growth tests were only conducted for the HSPT + PC + Bimodal and HSPT + PC + Globular microstructures, as ΔK_{th} values for the HSPT,