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Effect of microstructure on the fatigue properties of Ti–6Al–4V titanium alloys

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ABSTRACT

Through an analysis on microstructure and high cycle fatigue (HCF) properties of Ti–6Al–4V alloys which were selected from literature, the effects of microstructure types and microstructure parameters on HCF properties were investigated systematically. The results show that the HCF properties are strongly determined by microstructure types for Ti–6Al–4V. Generally the HCF strengths of different microstructures decrease in the order of bimodal, lamellar and equiaxed microstructure. Additionally, microstructure parameters such as the primary α (α_p) content and the α_p grain size in bimodal microstructures, the α lamellar width in lamellar microstructure and the α grain size in equiaxed microstructures, can influence the HCF properties.

1. Introduction

Due to their excellent properties (high specific strength, high fatigue strength, good corrosion resistance, etc.), titanium components (particularly Ti–6Al–4V) are often used for manufacturing critical systems such as airfoils, undercarriage components, and airframes [1–4] instead of heavy steel components. During these applications titanium structures are often exposed to fatigue loading [1]. Fatigue fracture is an important failure mode for these structures [5].

Depending on the alloy class, the parameters possibly having an influence on the fatigue life of titanium alloys include grain size (phase dimension and morphology), age hardening condition, degree of work hardening, elastic constants, and crystallographic texture [1]. Depending on the thermomechanical treatment or heat treatment of the $(\alpha + \beta)$ titanium alloy, such as Ti–6Al–4V, the microstructure and mechanical properties can vary in a wide range [3,6]. Such influences have been documented in numerous reports in the literature [4,7–11]. However, due to experimentation limitations, experimental results are not always reproducible, and thus it is difficult to compare among fatigue properties obtained from different tests, even for a same microstructure. There has not been enough data to correlate fatigue properties based on differing microstructures. Based on the comparison of microstructure types of Ti–6Al–4V alloys, Hines and Nalla [12,13] pointed out that lamellar microstructure had higher HCF strength than bimodal microstructure. However, Zuo et al. [10] and Niinomi et al. [14] obtained the opposite result. Ivanova et al. [15] and Peters and Lütjering [16,17] proved that bimodal microstructure had higher HCF strength than the equiaxed microstructure, and Peters and Lütjering [17] showed that lamellar microstructure also had higher HCF strength than the equiaxed microstructure. However, it was also reported [2] that equiaxed microstructure had the highest HCF strength, and according to Ivanova and Adachi [18,19], lamellar microstructure had a similar HCF strength to bimodal microstructure. The reasons for this contradiction have not been well explained. Additionally, the fatigue strength would be dependent on microstructural parameters of each Ti–6Al–4V alloy, such as the α_p content and α_p grain size in bimodal microstructure [15,18,20], the α grain size in the equiaxed microstructure [2,18,21], and the lamellar α width in lamellar microstructure [10,12,13].

So, there is differing information in the literature concerning the relative strengths of Ti–6Al–4V alloys based on microstructure type. These authors did not necessarily use the same bimodal, lamellar, and equiaxed microstructures. These differences can make sense if we incorporate the parameters that are listed.

However, the influence of the microstructural parameters on fatigue property is difficult to investigate systematically, because the fatigue test costs a lot of human and material resources. A more comprehensive evaluation of the influence of the individual microstructure parameters on fatigue properties is difficult, because all data presented in a paper are from one research group. This also limits the ability to evaluate additional effects due to variations in specimen preparation, test procedure, micro-alloy composition differences, heat treatment, rolling or forging procedure affecting texture, etc. [22].

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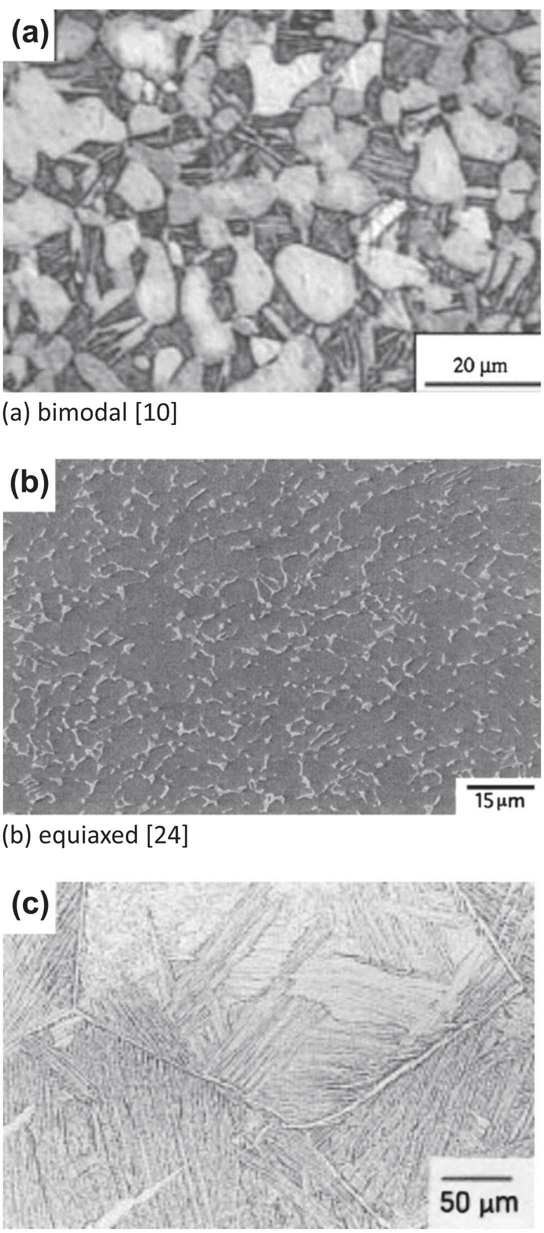
Through an analysis on microstructures and HCF strengths of the Ti–6Al–4V alloys based on the literature dated from 1972 to present, effects of microstructure types and microstructure parameters on HCF properties were investigated systematically. The influences of the microstructure types (bimodal, lamellar, equiaxed) on the HCF properties were investigated. Additionally, the effects of the microstructure parameters (α_p content and α_p grain size, lamellar width) on the HCF properties were investigated.

2. Method

In this paper, 75 sets of data in 21 references [10,12–15,17–21,23–33] were collected with information about the HCF strength data and microstructure parameters of Ti–6Al–4V alloys according to microstructure types (Fig. 1 and Tables 1–3). No testing was done by the authors but the work relied entirely on the literature data. All fatigue tests were performed in room-temperature air under axial loading conditions with a sine wave on smooth-bar, unnotched hourglass specimens.

Most of the microstructural parameters (α_p content, α_p grain size and lamellar width) can be obtained from literature, but the ones that are not given clearly are analyzed by the Nano Measurer1.2 software according to the SEM images in the references. All these measured parameters are labelled as 'a' in Tables 1–3. α grain size was measured by linear intercept method [34], and α lamellar width was measured by the way described in [35]. Fatigue strength data were obtained from the stress–life (S–N) curves in the literature.



(a) bimodal [10]

(b) equiaxed [24]

(c) lamellar [12]

Fig. 1. Three typical microstructures.

Table 1
Database of bimodal microstructure parameters and HCF data of Ti–6Al–4V alloys.

No.	Ref.	Bimodal (μm)		Frequency (Hz)	Stress ratio (R)	HCF strength (MPa)		
		V_α	D_α			10^5	10^6	10^7
1	Bellows et al. [25]	60	13[a]	60	−1	450	400	390
					0.1	667	611	556
					0.5	860	800	640
					0.8	950	920	900
2	Hines and Lütjering [12]	35	7.5[a]	90	−1	545	470	445
3	Ivanova et al. [15]	60.5	8	30	0.1	–	–	467
		24.8	8.5			830 (3×10^4)	620 (2×10^6)	550
4	Nalla et al. [13]	64	20	25	0.1	700	600	540[b]
					0.5	850	780	640[b]
5	Peters and Lütjering [17]	60	20	90	−1	480	400	375
6	Zuo et al. [10]	55	10	20,000	−1	–	546	518
7	Oguma and Nakamura [20]	–	4	120	0.1	900	865	850
		–	10			860	810	650
8	Nagai et al. [26]	–	4	20	0.01	800	720	640
		–	4[c]			800	720	690
		–	2.8			800	740	720
9	Broichhausen and Kann [27]	–	–	–	−1	588	547	539
10	Peters et al. [21]	–	6	80	−1	710	675	675
11	Hines et al. [28]	–	9.7[a]	90	−1	470	400	380
		–			0.1	700	550	500
		–			0.5	–	–	650
12	Ivanova et al. [18]	60.5	8	30	−1	462	441	414
		24.8	8.5			455	421	407
		28.7	5.5			510	497	490
		60.5	8		0.1	720	582	491
		24.8	8.5			720	613	551
		28.7	5.5			798	751	720
13	Rudinger and Fischer [29]	20[c]	–	130	0	725	700	680
			–			–	775	580
		50	–			700	590	480
14	Adachi et al. [19]	40[c]	10	90	−1	–	–	550
					0.2	–	–	700
					−1	–	–	540
					0.2	–	–	600
			6		−1	–	790	770
					0.2	1125	1075	1050
					−1	740	730	730
					0.2	1100	875	800
15	Nalla et al. [30]	64	20	5	−1	450		
16	Nakanura et al. [31]	–	4	120	−1	660	660	660
		–			−0.5	827	827	827
		–			0.1	911	878	844
17	Zuo et al. [32]	55	10	25	−1	570	530	–

[a] Measured by the authors.
[b] Frequency is 1000 Hz.
[c] Fatigue specimens with different textures.