Microstructure Dependence of Fatigue Behaviour in Beta Ti-22V-4Al Alloy

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ABSTRACT: *The effects of microstructure on fatigue behaviour in beta Ti-22V-4Al alloy are studied. A wide variety of microstructures were prepared with heat treatment, which were classified into three groups, as-solution treated materials, solution treated and aged materials, and duplex-aged materials. Rotary bending fatigue tests have been conducted using smooth specimens in laboratory air at ambient temperature. Based on obtained experimental results, the role of microstructural variables such as grain size and alpha precipitates in fatigue behaviour is discussed. Particular attention is paid to subsurface crack initiation.*

INTRODUCTION

Beta titanium alloys are considered for extensive engineering applications in which fatigue properties are critical, because of many attractive properties such as high strength to density, good cold formability and weldability, and excellent corrosion resistance [1]. Studies on beta titanium alloys have concentrated to establish the relationships between static mechanical properties and microstructure, thus there have been limited studies on fatigue behaviour [2-9], particularly crack initiation and small crack growth [7,8]. Since a wide variety of microstructures can be produced with thermomechanical treatments, it is very important to realize the role of microstructural variables in fatigue behaviour.

In the present study, rotary bending fatigue tests were conducted using smooth specimens of materials having various microstructures in beta Ti-22V-4Al alloy. Fatigue strength was evaluated and the effects of microstructure on fatigue behaviour are discussed on the basis of crack initiation and small crack growth behaviour and SEM fracture surface analysis.

EXPERIMENTAL DETAILS

Material, Microstructures and Mechanical Properties

The material used is beta Ti-22V-4Al alloy whose chemical composition (wt.%) is V 22.7, Al 3.8, Fe 0.12, O 0.15, N 0.03, C 0.01. Heat treatment conditions are listed in Table 1. The materials prepared are classified into three groups, as-solution treated materials (ST), solution treated and aged materials (STA), and duplex-aged materials (STDA). The ST materials had equiaxed beta grain structures (ST750 and ST850). The STA materials were solution treated at four different temperatures above the beta transus, T_β, of 720ºC followed by aged (STA750, STA800, STA850 and STA950) and had microstructures with alpha precipitates within the beta matrix. All the STDA materials were solution treated at 750ºC and then duplex-aged: the five different first-ageing temperatures, $T_{a,1}$, were employed and the second-ageing temperature, $T_{a,2}$, was fixed, which was the same as the STA materials. In STDA300 and STDA350, fine alpha precipitates were uniformly dispersed with some large precipitates, while STDA500, STDA550 and STDA600 had bi-modal microstructures with large and fine alpha precipitates. The mechanical properties are given in Table 2.

TABLE 1: Heat treatment conditions.

Material code	Solution treatment [a] (ºC /h)	Ageing treatment [b] (ºC /h) 1st step	2nd step	Grain size (μm)
ST750	750/1			31
ST850	850/1			58
STA750	750/1	450/8		31
STA800	800/1			32
STA850	850/1			58
STA950	950/1			165
STDA300	750/1	300/32	450/8	31
STDA350		350/32		
STDA500		500/4		
STDA550		550/4		
STDA600		600/4		

[a] followed by water cooling,
[b] followed by air cooling

TABLE 2: Mechanical properties.

Material code	Tensile strength σ_B (MPa)	Elongation ϕ (%)	Reduction of area ϕ (%)	Vickers hardness *HV*
ST750	669	18	59	239
ST850	651	16	65	242
STA750	1279	1	13	380
STA800	1430	2	4	392
STA850	1464	2	6	401
STA950	1244	2	6	460
STDA300	1366	4	8	348
STDA350	1348	2	9	366
STDA500	1257	7	15	370
STDA550	1109	7	43	339
STDA600	920	7	50	312

Procedures

Fatigue specimens with a reduced diameter of 5.5 mm were used, which were mechanically polished and then electropolished. Fatigue tests were conducted on a rotary bending fatigue testing machine (frequency: 57 Hz) in laboratory air at ambient temperature. Crack initiation and growth were monitored with replication technique. After experiment, the crack initiation site was examined in detail using a scanning electron microscope (SEM).

RESULTS

Fatigue Strength

The *S-N* curves of the ST materials are shown in Fig.1(a). The fine-grained material (ST750) exhibits higher fatigue strength than the coarse-grained material (ST850). The *S-N* curves of the STA materials are also included in Fig.1(a). It should be noted that the STA materials except for STA950 show definite step-wise *S-N* curves consisting of short life regime and long life regime. The grain size dependence of fatigue strength is obscure, but fatigue strength tends to increase slightly with increasing grain size. As will be described later, cracks initiated at the interior of specimens in long life regime. STA950 with the largest grain size has the lowest fatigue strength and no subsurface fracture was observed.

Figure 1(b) represents the *S-N* diagram for the STDA materials. For comparison, the *S-N* curve of STA750 is included. In the low-high duplex-aged materials, the fatigue strength of STDA350 is higher than that of STDA300, and is higher or slightly lower than STA750 in short and long life regimes, respectively. In the high-low duplex-aged materials, fatigue strength decreases with increasing $T_{a,1}$. The fatigue strength of STDA500 is slightly higher than that of STA750. STDA550 has lower fatigue strength than STA750 and STDA600 shows considerably lower fatigue strength. Note that no subsurface fracture occurred in all the materials.

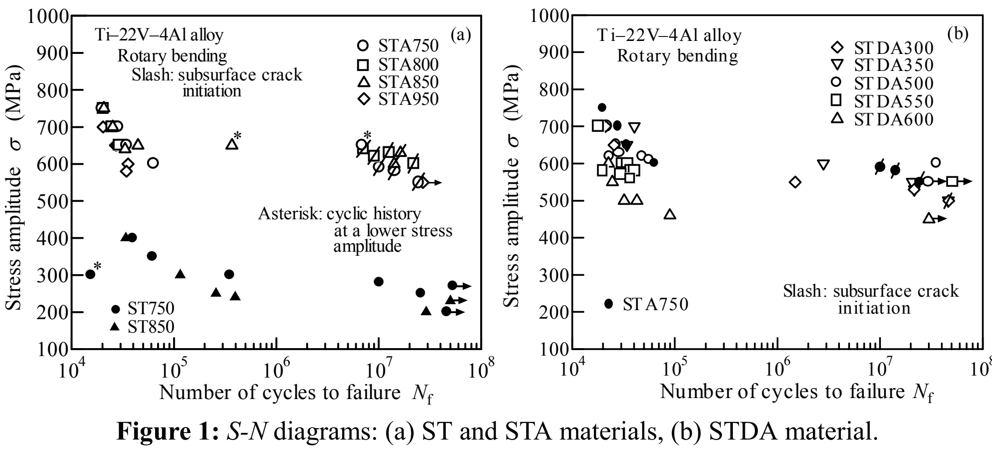

Figure 1: *S-N* diagrams: (a) ST and STA materials, (b) STDA material.

Fatigue Crack Initiation

Surface crack initiation and growth

In the ST materials, cracks initiated from slip bands within grains. All the STA materials showed grain boundary-related crack initiation at the surface in short life regime and a flat facet was seen at the initiation site. In the low-high duplex-aged materials, crack initiation was grain boundary-related, while in the high-low duplex-aged materials, within grains, and thus a flat facet or a stage I facet was observed, respectively.

The relationships between surface crack length, 2*c*, and cycle ratio, N/N_f, are shown in Fig.2. In the ST materials, cracks initiate at very early stage of fatigue life, thus most of fatigue life is spent by small crack growth. On the contrary, cracks in the STA materials generate at 70 % to 80 % of fatigue life independent of solution treatment temperature, T_s, indicating that the crack initiation process dominates fatigue life. The STDA materials indicate the intermediate crack initiation behaviour between the ST and STA materials and cracks initiate at 40 % to 60 % of fatigue life, thus crack initiation and growth stages are nearly the same fraction of fatigue life.

Figure 3 represents the relationships between crack growth rate, da/dN, and maximum stress intensity factor, K_{max}. In the ST materials, fluctuation of crack growth rate is seen in very small crack region due to grain boundary blocking effect. The crack growth behaviour of the STA materials is similar independent of T_s. In addition, it should be noted that the STA materials show almost the same growth behaviour as the ST materials, indicating no significant influence of ageing treatment. The STDA materials exhibit nearly the same crack growth behaviour regardless of duplex ageing condition, which is also the same as the ST and STA materials. Therefore, it is concluded that ageing condition does not alter the small crack growth resistance.

Subsurface crack initiation

In long life regime, subsurface fracture occurred in the STA materials except

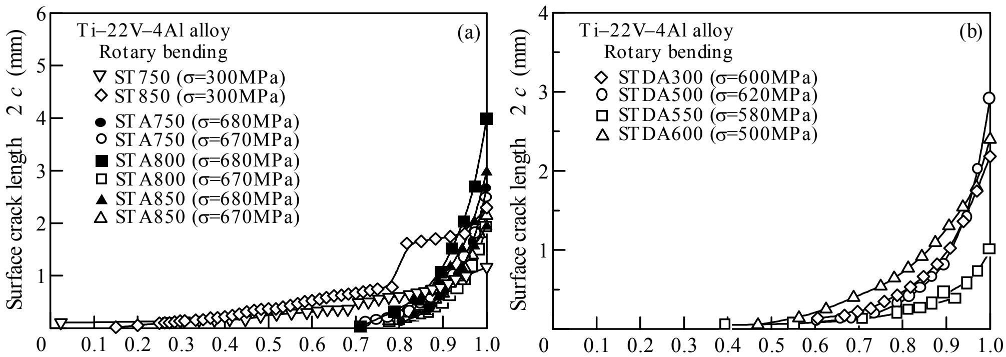

Figure 2: Relationships between surface crack length and cycle ratio: (a) ST and STA materials, (b) STDA material.

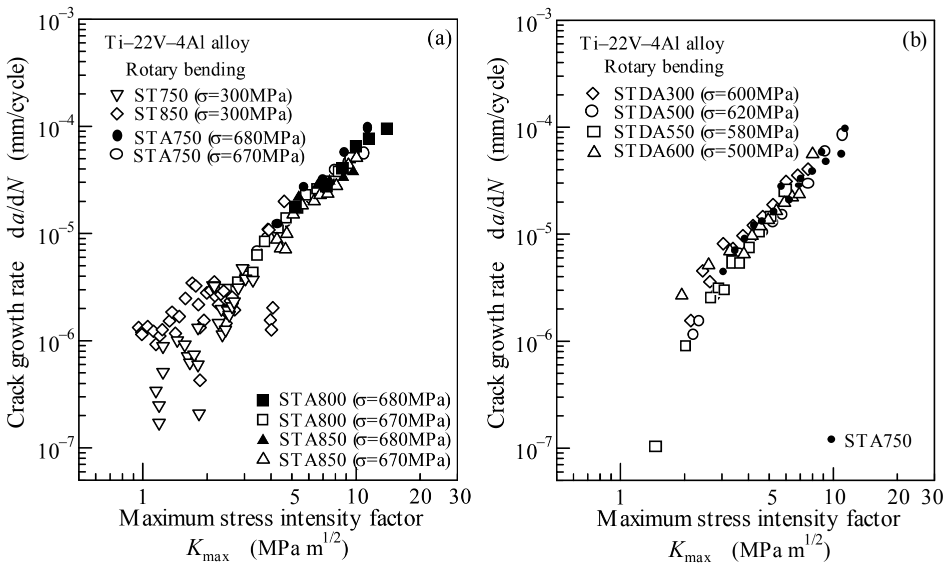

Figure 3: Relationships between small crack growth rate and maximum stress intensity factor: (a) ST and STA materials, (b) STDA material.

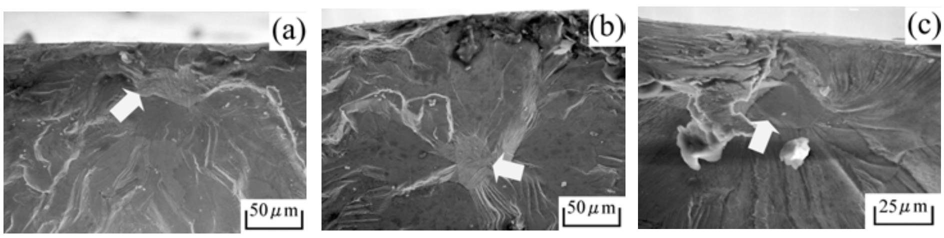

Figure 4: SEM micrographs showing subsurface crack origin in STA materials: (a) STA750 (σ=590MPa, N_f=1.01×10^7), (b) STA800 (σ=640MPa, N_f=7.15 ×10^6), (c) STA850 (σ=630MPa, N_f=1.63×10^7). Arrow indicates the facet.

for STA950 (Fig.1(a)). Figure 4 reveals typical examples of SEM micrographs of subsurface crack origin at which a flat facet was always seen in all the cases. From matching SEM examination in a pair of fracture surfaces, such a facet was present in both fracture surfaces.

DISCUSSION

Effect of Grain Size on Fatigue Strength in the STA Materials

The fatigue strength of the STA materials tended to increase slightly with increasing grain size, which may be affected by not only grain size itself, but also alpha precipitates, because tensile strength and hardness increased with increasing grain size (Table 2). It is thought that alpha precipitates exerted much larger influence than grain size did, thus the coarse-grained materials indicated higher fatigue strength. On the other hand, STA950 showed the lowest tensile strength and fatigue strength in spite of the increased hardness, due to its very large grain size of 165 μm. Figure 5 demonstrates a schematic illustration showing effects of grain size and alpha precipitates on fatigue strength. With increasing T_s, fatigue strength decreases due to increasing grain size, while it increases due to enhancing alpha precipitation. Consequently, the highest fatigue strength would be obtained for a certain grain size as a result of the superposition of both effects. Therefore, if one chooses T_s just above the T_β value so that remarkable grain growth does not occur, then microstructure that has excellent fatigue strength would be achieved. However, it should be noted that the STA materials indicated subsurface fracture in long life regime, which suggests that microstructural modification is further necessary.

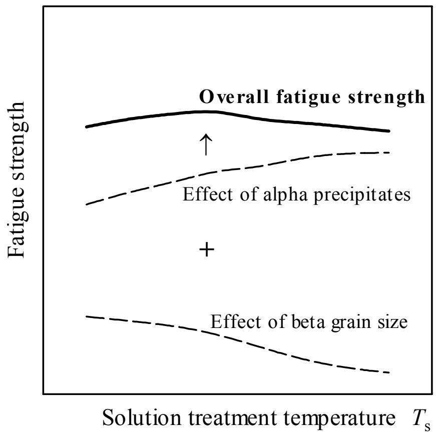

Figure 5: Schematic illustration showing effects of grain size and alpha precipitates on fatigue strength in STA materials.

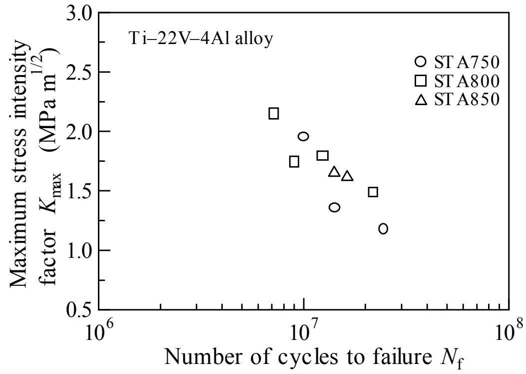

Figure 6: Relationship between maximum stress intensity factor for facets and fatigue life.

Subsurface Crack Initiation Mechanisms

Microstructural variables

A very significant feature is the presence of a flat facet at the crack initiation site. The facets seem to be grain boundary-related, but it is not clear whether they are grain boundary itself or grain boundary alpha phase. Although no differences were detected by EPMA analyses in the constituent elements between the facets and the matrix, the facets would be grain boundary alpha phases because of the existence of patterns of slip traces on their surface. It was found from SEM analyses that the incident angles of the facets were nearly 45° to the specimen axis. Therefore, it is believed that cracks initiated by slip deformation of soft grain boundary alpha phases.

Transition of crack initiation site from surface to interior

Grain boundary alpha phases are also present at the surface, which could be cyclically strengthened, thus the transition of the crack initiation site from the surface to the interior would occur. This is supported by additional fatigue test results shown in Fig.1(a). The data with asterisk in the STA materials were subjected to cyclic history of N=7×10^6 at a stress that causes subsurface fracture, which show considerably long fatigue lives compared with the data without cyclic history. In the ST materials, a cyclic history decreased fatigue life as shown in Fig.1(a). These results seem to indicate that some strengthening mechanisms such as diffusion of interstitials to alpha phase (strain ageing) and work hardening have operated.

A mechanical approach to subsurface fracture

Figure 6 shows the relationship between maximum stress intensity factor, K_{max}, for facets and fatigue life. Regardless of T_s, i.e. grain size, there is a good correlation between both, where fatigue life increases with decreasing K_{max}. This result implies that the crack initiation stage would be dominant in fatigue life. In fact, in the specimens subjected to cyclic history of N=7×10^6 cycles cracks generated at the surface, suggesting that at that cycles, subsurface crack initiation has not occurred yet. Furthermore, it has been indicated that more than 99 % of fatigue life was consumed in the crack initiation process in a beta titanium alloy [2].

Suppression of Subsurface Crack Initiation

Subsurface crack initiation was not seen in the STDA materials, indicating that it can be suppressed by duplex ageing. In the low-high duplex-aged materials (STDA300 and STDA350), since beta prime phase and omega phase precipitated during the first ageing act as a pre-cursor to alpha precipitation [4,8], alpha precipitation within grains is highly enhanced by the subsequent second ageing, thereby precipitation at grain boundaries would be decreased or minimized. On the other hand, in the high-low duplex-aged materials (STDA500, STDA550 and STDA600), coarse alpha phases are precipitated within grains by the first ageing at the higher temperatures, which are easily deformed by cyclic stress, then leading to crack initiation. Therefore, subsurface crack initiation was suppressed.

CONCLUSIONS

(1) In the as-solution treated materials (ST), the fine-grained material showed higher fatigue strength than the coarse-grained material, while in the solution treated and aged materials (STA), fatigue strength increased slightly with increasing grain size.

(2) The STA materials showed step-wise *S-N* curves consisting of short life regime and long life regime, being due to different crack initiation mechanisms: surface crack initiation and subsurface crack origin. No subsurface fracture was seen in the ST materials.

(3) Surface crack initiation was strongly influenced by ageing condition, while small crack growth was independent of ageing condition.

(4) In the STA materials, a flat facet was always seen at the subsurface crack initiation site and there was a good correlation between maximum stress intensity factor for facets and fatigue life, where fatigue life increased as maximum stress intensity factor decreased.

(5) Fatigue strength was improved by duplex ageing when the first ageing temperature was close to the second ageing temperature, and subsurface fracture was completely suppressed by duplex ageing.

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