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Crack Nucleation in β Titanium Alloys under High Cycle Fatigue Conditions - A Review

Crack Nucleation in β Titanium Alloys under High Cycle Fatigue Conditions - A Review

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Abstract. Beta titanium (β-Ti) alloys have emerged over the last 3 to 4 decades as an important class of titanium alloys. Many of the applications that they found, particularly in aerospace sector, are such that their high cycle fatigue (HCF) behavior becomes critical. In HCF regime, crack nucleation accounts for major part of the life. Consequently it becomes important to understand the mechanisms underlying the nucleation of cracks under HCF type loading conditions. The purpose of this review is to document the best understanding we have on date on crack nucleation in β-Ti alloys under HCF conditions. Role of various microstructural features encountered in β-Ti alloys in influencing the crack nucleation under HCF conditions has been reviewed. It has been brought out that changes in processing can result in changes in microstructure which in turn influence the time for crack nucleation/fatigue life and fatigue limit. While majority of fatigue failures originate at the surface, subsurface cracking is not uncommon with β-Ti alloys and the factors leading to subsurface cracking have been discussed in this review.

Keywords: β **Titanium alloys, Fatigue crack nucleation, Super-transus and sub-transus processing, Grain boundary alpha, Subsurface crack nucleation, Duplex aging, Precipitate free zones**

1. Introduction

1.1. Importance of β Titanium Alloys

Beta titanium (β -Ti) alloys constitute an important class of titanium alloys; they offer the highest strength to weight ratio and very attractive combinations of strength, toughness and fatigue resistance [1]. Some grades are produced as forged components, while some others are produced as strips. Through the aging process a wide range of yield strengths can be obtained in β-Ti alloys. An important benefit provided by a beta structure is the increased formability of β-Ti alloys, relative to α and α+β alloys [2]. β-Ti alloys have been widely used in the aerospace industry - load-bearing fuselage components and high-lift devices of Russian aircraft, forgings for airframe and landing gear applications, such as for Boeing 787, springs and fasteners [3]. Table 1 gives details of β-Ti alloys which have been the subjects of detailed investigation for high cycle fatigue (HCF) behaviour.

1.2. Importance of the HCF Strength of β titanium alloys
High cycle fatigue properties and the fatigue limit are important considerations in design of structural parts in many aerospace applications [4, 5]. The majority (>50%) of fatigue fractures in all manufactured components are caused by HCF failures, particularly in the aerospace industries [6]. Accordingly much of the research on β-Ti alloys has been dedicated to develop new grades with high HCF life or improve the HCF life of the existing grades.

1.3. Importance of Crack nucleation phase in determining the HCF life
It is well known that fatigue crack initiation process occupies the main portion of the total fatigue life of the material in the HCF regime (fatigue life larger than $10^4 - 10^5$ cycles) [7]. Thus the HCF strength is a good measure of the resistance of the material to crack nucleation under HCF loading conditions. Lower HCF strength indicates that crack nucleation is easy; materials offering high resistance to fatigue crack nucleation under HCF loading conditions have a high HCF strength [8]. The present review of fatigue crack initiation in β-Ti alloys under HCF conditions is thus directly relevant to the HCF life of these alloys.

1.4. Solution Treated and Aged Condition vs Solution Treated Condition
The standard heat treatment of β-Ti alloys comprises of solution treatment and aging (STA) [2, 3]. Solution treatment may be super-transus (at a temperature higher than β-transus) or sub-transus (at a temperature below β-transus) [9]. Most of the applications for β-Ti alloys involve service in STA condition, because of the high strength they have in this condition. After solution treatment (ST) but before aging, they do not possess high strength. Hence the ST condition is not of much importance in practice. Hence this review gives more attention to the STA condition. Brief reference is however made to fatigue behavior in ST condition (Section III). Section II is a detailed treatment of fatigue behavior of β-Ti alloys in STA condition with super-transus solution treatment. Section IV deals with β-Ti alloys processed based on sub-transus solution treatment.

2. Crack nucleation in super-transus solution treated and aged condition
2.1. Microstructural features influencing the crack nucleation
Studies have shown that fatigue crack nucleation is controlled by different microstructural features, importantly grain boundary α, precipitate free zones (PFZs) and beta grain size.

2.1.1. Grain boundary alpha It is well known that soft α layers located at prior β grain boundaries are the most typical feature in metastable β-Ti alloys, which can dramatically decrease HCF properties of these alloys [10, 11]. It is widely believed that α phase is softer than the β matrix. As a result HCF damage is importantly governed by grain boundary α layers in metastable β-Ti alloys. Schmidt et al [5] showed that formation of grain boundary α in Ti 38-644 lowers the fatigue limit. Santosh et al [12] concluded that grain boundary α was facilitating easy and early crack initiation during fatigue loading of Ti 15-3 alloy. Kim et al [13], based on their studies on Ti 15- 3 alloy, concluded that concentrated stress in grain boundary region first causes the debonding between the favorably oriented (i.e. 45^o to loading axis) alpha and beta phases in the close vicinity of grain boundary. Studies by Kokuoz et al on TIMETAL-LCB [14] showed that damage accumulation within grain boundary α and fatigue crack nucleation are related. The authors also concluded that HCF behavior is controlled by the contiguity of the grain boundary α and that a higher degree of contiguity leads to higher chances of fatigue crack nucleation. In case of lamellar microstructures, the fatigue cracks usually nucleate at grain boundary α layers. Even in case of bimodal microstructure, grain boundary α layers serve as nucleation sites [11].

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2.1.2. Precipitate free zones Precipitate free zones are important microstructural features in β-Ti alloys. PFZs are soft zones in the microstructure and hence preferentially deform on application of load. They exert a strong effect on the fatigue and fracture behavior of Ti and Al alloys [15]. HCF life of β-Ti alloys is very sensitive to the presence of PFZs. In single aged condition, the PFZs were found to be the cause for early crack nucleation in Ti 38-644 under HCF conditions, resulting in a lower fatigue limit [5, 16]. The amount and size of PFZs in Ti 38-644 increased with aging temperature. Reduction in aging time at a constant temperature lead to increase in the volume fraction of PFZs [5]. Thus the aging temperature and time come importantly into play in determining the HCF life of the alloy. The micro-PFZs present in Ti15-3 were found to contribute to reduced resistance to fatigue crack nucleation [12].

2.1.3. Grain size An increase in solution treating temperature results in an increase of grain size in β-Ti alloys. A grain size reduction leads to increase in the fatigue strength of β titanium alloys as reported in [1]. Tokaji et al [17] reported that for β-Ti alloys in STA condition largest β grain size value is associated with considerably lower fatigue strength. Schmidt et al [5] reported that β grain size is the primary factor controlling the fatigue life of Ti 38-644. In the case of coarse grained beta structure, fatigue cracks always nucleated on the continuous alpha layers at beta grain boundaries [11] which was also confirmed by [14] and [5]. Reduction in grain size also resulted in increase in the HCF strength to Yield Stress ratio [11]. The operative slip length in the crack nucleation phase is proportional to the grain size; the resistance to fatigue crack nucleation is increased by a reduction of the slip length, i.e. by a reduction in β grain size [11]. The dependence of fatigue life on β grain size can thus be explained.

2.2. Effect of aging on crack nucleation - Single aging vs. Duplex aging
There is a drastic improvement in HCF life of Ti15-3 alloy on switching over from single aging to double aging [12, 18]. Similar improvement was reported by Schmidt et al for Ti 38-644 alloy[5]. After double aging Ti15-3 alloy, it was found that there were no PFZs in the microstructure and grain boundary α was present to a very small extent; in contrast, after single aging PFZs were present and there was a higher amount of grain boundary α [12]. Schmidt et al [5] also reported that duplex aging increases the ductility, suppresses the occurrence of PFZs and eliminates grain boundary α in Ti38-644. Duplex aging reduces the impact of PFZs and grain boundary α on fatigue crack nucleation. Consequently the crack nucleation time increases, leading to an increase in HCF life.

3. Crack nucleation in solution treated condition
HCF studies were carried out on three β-Ti alloys in solution treated condition [19]. The authors concluded that initial damage accumulation during HCF is associated with the formation of coarse, planar slip bands. Fatigue crack nucleation was associated with crack initiation at intersecting planar slip bands at or near the free surface. The increase in operative slip length occasioned by the presence of low-angle grain boundaries leads to accelerated crack nucleation. The authors concluded that the resistance to fatigue crack nucleation is inversely proportional to the square root of the operative slip length. Hu et al [20] carried out studies on fatigue crack nucleation in TIMETAL LCB in ST condition. They concluded that both slip bands and grain boundaries are the preferred sites for fatigue crack nucleation. They also found that high angle grain boundaries were preferred sites for intergranular fatigue crack initiation. Low angle grain boundaries were never found to be associated with formation of fatigue cracks.

4. Crack nucleation in materials produced by sub-transus processing
Huang et al [21] carried out HCF studies on Ti55531 alloy with a bimodal microstructure (BM) having 15% near globular α_p phase with an average grain size of 3 $\pm$ 1 mm, approximately 3%

continuous Grain Boundary Alpha phase with 200 ± 10 nm in width and a large volume fraction of secondary α (α_s) phase within the residual beta matrix. The authors demonstrated that the fatigue crack initiation occurs at severely deformed α_p particles below the surface and the direction of the initiation facet is inclined at about 43.8^o to the stress axis. Shear deformed bands or slip bands formed in the globular α_p phase promotes the nucleation of micro-voids, which would in turn play a significant role in the initiation of microcracks. Lenain and Jacques [22] studied the HCF behavior of TIMETAL LCB with a bimodal microstructure. They found that cracks initiate at the interface between α and β phases. Huang et al [23] also compared the HCF behavior of the alloy with bimodal microstructure (BM) and with lamellar microstructure (LM). Grain boundary α layers have more effect on promoting crack initiation in LM than in BM. As a result fatigue microcracks mainly initiate at the interface between grain boundary α films and prior β grains or at the secondary α/residual β interface for LM. However microcracks primarily nucleate at the α_p / transformed β interface or at α_p particles for BM. Shi et al [6] studied the crack initiation behavior and fatigue limit of Ti55511 alloy with different basket-weave features. They brought that difference in microstructure cause differences in crack initiation behavior, microstructure having primary α phase promoting subsurface nucleation. The differences in microstructure also cause differences in fatigue limit. Table 2 summarizes the microstructural features in β-Ti alloys which, as per published literature, serve as sites for crack nucleation during fatigue loading.

5. Factors influencing surface vs subsurface crack nucleation

There are different factors which can contribute to subsurface crack initiation in β-Ti alloys.

5.1. Effect of Grain Boundary Alpha and Precipitate Free Zones

The contribution of grain boundary alpha to subsurface crack initiation in single aged condition was reported by Santhosh et al in Ti 15-3 alloy [12]. Subsurface crack initiation was also reported by Schmidt et al in Ti38-644 and was attributed to extensive grain boundary α and the PFZs existing within the β grains [5]. Studies by Tokaji et al [17] also suggest that subsurface crack initiation in solution treated and aged β-Ti alloys occurs due to a slip-related fracture process on the grain boundary α phase.

5.2. Effect of primary α in sub-transus processed β-Ti alloys

Studies by Shi et al [6] showed that presence of coarse α phase in basket weave type microstructures in Ti55511 promotes subsurface crack nucleation. For microstructures without blocky α, crack nucleation is essentially at the surface. Subsurface crack initiation is also dominant in β-Ti alloys with bimodal microstructures, the primary α particles and interfaces of primary α particles and β matrix serving as preferred nucleation sites [21, 23].

5.3. Effect of aging

Santhosh et al [12] found instances of subsurface initiation on fatigue loading of single aged Ti15-3 material. On the other hand, crack nucleation in the material was found to have occurred at the surface in double aged specimens. Studies by Schmidt et al [5] concluded that fatigue crack initiation in Ti 38-644 alloy samples was subsurface in single aged materials; in contrast, initiation was associated with the surface in double aged condition. With the non-availability of potential crack nucleation sites beneath the surface in double aged condition, crack nucleation occurs at the surface. The aging temperature rather than aging time was found to be important in causing internal fatigue crack initiation in Ti15-3 alloy [13]. In unaged (solution treated) β-Ti alloys, no subsurface crack initiation was observed on fatigue loading [19]. This is believed to be a consequence of microstructural features which may cause subsurface crack nucleation such as grain boundary α, PFZs being absent in the microstructure.

5.4. Effect of shot peening

Shot peening is done in β-Ti alloys to harden the surface [2]. Shot peening induces changes in the surface layer properties [24]. Shot peening improves fatigue strength considerably at room temperature; on the other hand, at elevated temperatures, shot peening reduces fatigue strength [1]. Shot peening also resulted in an increase in surface roughness [25]. Fatigue crack nucleation was found below the surface after shot peening TIMETAL LCB alloy specimens [25]. This was interpreted in terms of the occurrence of high residual tensile stress regions below the surface. Studies by Dorr and Wagner [26] showed carried out shot peening experiments on two β-Ti alloys - Ti 10-2-3 in STA condition and Ti3Al8V6Cr4Mo4Zr in ST condition. The authors observed that fatigue cracks nucleated at the surface. Influence of shot peening in terms of shifting the nucleation site from surface to subsurface appears to depend on the process parameters used for shot peening and the condition of the starting material.

6. Conclusions

(i) Grain boundary α facilitates crack nucleation in β-Ti alloy microstructures obtained with both super-transus and sub-transus solution treatment. Triple points with continuous grain boundary α favor early fatigue crack initiation.

(ii) Presence of soft precipitate free zones (PFZs) in the microstructure leads to reduced resistance to fatigue crack initiation.

(iii) High angle grain boundaries are preferred location for fatigue crack initiation.

(iv) Reduction in β grain size reduces the slip length leading to an increase in resistance to fatigue crack initiation.

(v) Duplex aging delays fatigue crack nucleation by way of suppressing/ eliminating the potential crack nucleation sites - grain boundary α, PFZs

(vi) Crack nucleation in β-Ti alloys under fatigue loading can be surface or subsurface in nature. Microstructural features such as grain boundary α, PFZs, coarse primary α and surface treatments such as shot peening can lead to occurrence of subsurface crack nucleation.

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Table 1. Details of β-Ti alloys studied for their HCF behavior

Sl.No	Chemical Composition	Designation	Comments/Applications
1	Ti10V2Fe3Al	10-2-3	High strength forgings
2	Ti15V3Cr3Sn3Al	Ti15-3	Sheet, plate, airframe castings
3	Ti5V5Mo5Al1Cr1Fe	VT22/55511	High strength forgings
4	Ti5Al2Sn2Cr4Mo4Zr1Fe	β-CEZ	High strength, medium temperature applications
5	Ti4.5Fe6.8Mo1.5Al	TIMETAL LCB	Spring suspension applications in automotive sector
6	Ti3Al8V6Cr4Mo4Zr	38-644/Beta C	Oil fields, springs, fasteners

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Table 2. HCF Crack nucleation sites in β-Ti alloys

Sl.No	Site designation	β-Ti alloys where the site is active as per published literature
1	Grain boundary α	Different types of β-Ti alloys
2	Precipitate free zones	Ti15-3, 38-644 in super transus solution treated and single aged condition
3	Primary α	Ti 55511 subtransus heat treated with bimodal microstructure
4	Secondary α	Ti 55511 heat treated to a lamellar microstructure