Microstructural Effects on Fatigue Crack Growth of Cast and Forged TiAl Alloys

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Abstract

Fatigue crack growth and tensile experiments were conducted on three TiAl alloys in the cast duplex 47-XD, cast nearly fully lamellar 45-XD and wrought fully lamellar 47-5 at 25 and 650°C. The microstructures were fully characterized defining the extent of lamellar colony size, lath spacing presence of other phases. The tensile experiments showed the two lamellar structures to be stronger while the duplex alloy maintained a significantly higher fracture toughness at elevated temperatures. Fatigue crack growth threshold tests showed negligible difference between the three alloys and microstructures, having a K_{th} = 6 to 8 ksi $\sqrt{\text{in}}$. The need is exposed for an alternate failure design criteria to take advantage of γ -TiAl, where low densities and high threshold stress intensities hold advantage in light weight and durability not attainable in conventional nickel base alloys.

Introduction

Titanium aluminides based on the γ phase TiAl are being seriously considered for various applications in aero gas turbine engines. One serious consideration in implementation of these alloys is their low ductility and damage tolerance. Before consideration can be given to their implementation in highly stressed flight critical applications such as compressor or turbine blades, vanes or disks; a thorough understanding of flow growth characteristics will need to be attained.

In spite of this urgent requirement, relatively little attention has been given to the microstructural factors affecting fatigue crack growth in these complex alloys. A number of reviews have focused on the microstructural influences on tensile properties and fracture toughness [1-3]. These studies of fatigue crack growth characteristics in γ -TiAl have concentrated on either the duplex or fully lamellar structures without directly comparing the two [4-10]. Recent results have shown that the fully lamellar structures are more resistant to fatigue crack growth, especially at lower stress intensities, than the duplex microstructures [5-7]. The orientation of the lamellar colony with respect to the crack plane was found to play a strong role in crack growth rate. Trans-lamellar cracks were observed to propagate rapidly between lamellae only to stop and blunt at lamellar interfaces [5]. Those cracks which ran along lamellar interfaces propagated at a much more rapid rate. Fatigue crack closure was found to be minimal under ambient conditions and more significant at elevated temperatures due to oxidation induced closure [4,6].

A study is described here, which begins to fulfill the requirement of investigation and characterization of fatigue crack growth and fracture in two cast and one forged γ alloys being considered for rotating aircraft engine components. Through observation of fracture and fatigue crack growth characteristics with γ -TiAl microstructural variations, a clearer understanding of the influence of these factors are obtained.

Design Criteria

Fracture

For current materials, fracture critical components are designed and life managed under the Engine Structural Integrity Program (ENSIP) program which requires the damage tolerance of materials with respect to intrinsic or service generated defects must be demonstrated. This typically involves using an inspectable flaw size (determined by NDE) and calculated stress levels to determine remaining fracture (crack growth) life. This life is then used to set an inspection interval. However, for brittle materials, there is a narrow interval between the threshold stress intensity, ΔK_{th} , and the fracture toughness, K_{IC} , the crack growth rate curves are extremely steep, especially at room temperature [11]. Thus, the fraction of total design life resulting from crack propagation is small, and the inspection intervals, if any, are too frequent to be practical.

As a result, a new method of addressing ENSIP for brittle materials might be required, such as the use of ΔK_{th} as a life prediction criteria. In such a case, the service loads would have to be kept below K_{th} for a given initial flaw size to prevent the rapid propagation to failure of cracks initiated at flaws [7]. Designing below threshold would theoretically result in infinite life ($>10^5$ cycles), thus eliminating the need for design intervals.

Fatigue

For current materials, Low Cycle Fatigue (LCF) is also managed under the auspices of the ENSIP program. Low cycle fatigue is generally caused by engine start/stop or throttle cycles which occur at low frequency. Crack initiation is defined as a 1/32" (1 mm) long surface crack. P&W and the USAF define the acceptable probability of occurrence of an LCF crack as 1 crack occurring in a sample size of 1000 (1/1000 or B.1) having a 1/32" (1 mm) long crack at the predicted minimum life. Stress vs. life data can be regressed with a variety of equations; one of the most popular is the strain range/mean stress design system approach. This current approach covers a wide range of stress concentrations, temperature effects, stress ratios and the mean stress shift due to yielding. These methods, however, are geared to data which exhibits the following: low cycles to failure at high stresses and high cycles to failure at low stresses. Usually, an endurance limit approach, such as is popular with HCF, is avoided as too conservative. Data may exhibit some degree of scatter at individual stress levels, but not excessively. With the brittle gamma though, the data is relatively flat (high stresses result in few to many life cycles) and exhibits material scatter than scans 4 orders of magnitude (Figure 1).

As a result, new methods of addressing ENSIP for brittle materials in LCF might be required. In particular, similar to the crack growth rate case of designing below the threshold stress intensity, an LCF design system might involve designing to below an endurance stress limit. In this method, one would still design to a 3 sigma minimum endurance limit, and this would hopefully be considered a 'safe' limit. However, in reality, since the gamma LCF curves are so flat, and especially since there

Fig. 1 Gamma LCF data vs. conventional design methods.

is a wide amount of scatter in life with very little difference in stress, the endurance limit approach might not be conservative enough if there's only limited testing, as is currently the case. Also in the endurance limit approach, there is a risk of being too conservative in the high stress, low life area, which might reduce the weight advantages of using gamma.

Experimental Procedures

Three alloys were selected for study¹: 47-XD (Ti, 47Al, 2Mn, 2Nb, 0.8B), 45-XD (Ti, 45Al, 2Mn, 2Nb, 0.8B) and 47-5 (Ti, 47Al, 2Cr, 2Nb, 0.8B). The XD alloys are investment cast alloys which were HIP'ed to close casting porosity in the α/γ two phase region and stabilized in the α_2/γ two phase region. The 47-5 alloy was two step forged and solution heat treated in the α region and stabilized in the α_2/γ two phase region.

The microstructures were characterized under both optical and SEM microscopy to determine grain size, and α_2/γ lamellar spacing and grain boundary configuration. Preliminary tensile tests were conducted in air at ambient and 650C to guide FCG loading. Fatigue specimens were machined in a compact tension configuration. Fatigue crack growth tests were conducted in a servo-hydraulic testing machine using an R-ratio of 0.1 at 20 Hz at ambient and 650C. Fatigue crack growth measurements were made optically. The fracture surfaces were characterized utilizing SEM and crack propagation features correlated with stress intensity factor.

Results and Discussion

Microstructural Characterization

Results of the metallographic examination are summarized in Table I. The 47-XD alloy contained a duplex microstructure, DP, consisting of both single phase γ grains as well as grains composed of α_2/γ lathes. The lath grains composed approximately 40% of the structure and were 100 μm in diameter while the single phase γ grains were 30-50 μm in diameter and dispersed among the lath colonies. Along with these two majority phases, a fine dispersion of borides was observed uniformly distributed through out the structure. These borides took on three morphologies, discrete (0.1-0.3 μm in diameter), filamentary (1 x 0.05 μm) and blocky (ranging as large as 1 x 5 μm). Fig. 2 gives a typical view of this microstructure. The 45-XD specimens were nearly fully lamellar microstructure, NFL, having a grain size of 50 μm . A few single phase γ grains were observed, but they composed less than 5% of the materials volume and were on the order of 10 μm in diameter. The borides were all either discrete or filamentary in these specimens, on the

same order in size as those in the 47-XD alloy, with no blocky borides found. Fig. 3 is an optical micrographs of this alloy detailing boride distribution. The 47-5 alloy is shown in Fig. 4. Here the grains range from 200 μm . The microstructure is in the fully lamellar, FL, form. The borides in this alloy were discrete to acicular and having dimensions ranging from 1x1 to 1x6 μm . Additionally, a number of boride stringers, remnant from forging and clearly visible in Fig. 4, were found throughout the structure.

Fig. 2 Micrograph of 47-XD alloy showing the duplex cast microstructure of single phase γ grains with α_2/γ lath colonies, along with filamentary and discrete borides.

Tensile and Fatigue Crack Growth Testing

The results of tensile and fatigue crack growth threshold results are given in Table II. Under tensile conditions the 45-XD alloy is considerably stronger than either the cast 47-XD or the wrought 47-5 alloys.

¹ All Compositions are given in atomic per centages.

Fig. 3 Micrograph of 45-XD alloy showing the nearly fully lamellar cast microstructure of with α_2/γ lath colonies with only small remnants of single phase γ grains, along with filamentary and discrete borides.

Fig. 4 Micrograph of 47-5 alloy showing the nearly fully lamellar wrought microstructure of with α_2/γ lath colonies with only small remnants of single phase γ grains, along with discrete and blocky borides.

Table I Summary of Alloy Microstructures

Alloy	Micro.	Vol. % Lath	Lath Spacing (μm)	Lath GS (μm)	γ GS (μm)	Discr. (μm)	Boride Filament (μm)	Blocky (μm)
47-XD	DP	40%	2.0	100	30-50	0.1-0.3	1x0.5	1-5
45-XD	NFL	>95%	3.0	50	10	0.1-0.3	1x0.5	
47-5	FL	100%	0.5	200			6x1	

Surprisingly, both cast alloys displayed higher elongation than the wrought alloy. Threshold stress intensity for all of these alloys was comparable at 25 and 650°C, with the wrought alloy displaying a slightly enhanced resistance to slow crack growth at ambient conditions. Fatigue crack growth curves represented as da/dn vs. ΔK are given for these three alloys at 25 and 650°C in Figs. 5-7.

Alloy 45-XD, a NFL structure, maintained significantly greater yield and ultimate strengths than either of the other alloys in the conditions tested. This was followed by the FL 47-5 alloy in strength at all but the 650°C ultimate strength where the NFL 47-5 and DP 47-XD alloys were comparable. These results are consistent with data reported in the literature [12-14] which have shown that, fully lamellar structures can maintain strengths approaching and surpassing duplex material, if the grain size is maintained below 500-1000 μm . If, however, the NFL and FL lamellar colony size is minimized, tensile strength and ductility are enhanced. The addition of boron to these cast alloys is known to minimize grain growth to a large extent and resulted in a relatively fine grain, 50 to 200 μm , fully lamellar structure.

As expected, the fully lamellar 47-5 alloy displayed a lower strain to failure at both ambient and elevated temperatures than the two cast alloys, due to its somewhat larger grain size.

Cyclic fracture toughness for the three alloys and microstructures studied here were comparable under ambient conditions; while the 47-XD alloy in the duplex microstructure displayed a near doubling in toughness at 650°C to nearly 20 $\text{ksi}\sqrt{\text{in}}$. The FL and NFL alloys (alloys 47-5 and 45-XD respectively) maintained a moderate fracture toughness of approximately 10-13 $\text{ksi}\sqrt{\text{in}}$, consistent with the literature values of other alloys in the NFL and FL structure [1,2].

Fig. 5 da/dn curve for alloy 47-XD at 25°C and 650°C.

Fig. 6 da/dn curve for alloy 45-XD at 25°C and 650°C.

Fig. 7 da/dn curve for alloy 47-5 at 25°C and 650°C.

Table II Tensile and Fatigue Crack Growth Threshold Results

Alloy	Temp. (°C)	Yield Stress (ksi)	Ultimate Stress (ksi)	Failure Strain (%)	Fracture Toughness (ksi√in.)	Threshold Stress Intensity (ksi√in.)
47-XD	25	57	73	1.3	10	7.5
47-XD	650	49	75	3.9	19	6.5
45-XD	25	85	100	1.5	13	7.3
45-XD	650	70	96	2.8	9	6.2
47-5	25	65	83	0.8	10	7.9
47-5	650	62	74	0.8	9	6.2

The threshold stress intensity was very consistent between the these three alloys. At ambient temperatures, where little closure is anticipated, ΔK_{th} ranged between 7.3 and 7.9 ksi√in. At elevated temperature, where closure due to oxidation of the crack tip has been observed [4], ΔK_{th} ranged between 6.2 and 6.5 ksi√in. The literature has indicated the fully lamellar structure to be more resistant to crack growth than the duplex structure [8]. This was not observed here, and may be attributed to the larger grain sizes, approximately 400 μm, tested in [8] for the fully lamellar structure. This is somewhat surprising given the wide differences in processing and microstructure. Other researchers have shown substantial differences in K_{th} dependent on microstructure [7].

Fractography

Four of the failed compact tension (CT) fatigue crack growth specimens were selected for fractographic examination. The specimens were examined at crack lengths yielding approximately equal stress intensities. The specimens are described in the Table III. The fractographic comparisons of 47-XD alloy provide information about the effects of temperature. The three room temperature fracture examinations provide information about the effect of alloy/microstructure/thermal mechanical processing on microscopic fracture mode.

The 47-XD alloy microstructure was clearly mirrored in the fracture topology. Some of the fine grains exhibited a lamellar structure, and

others showed no apparent structure. The later grains are assumed to be equiaxed γ grains. At 26°C, these fine grained areas occasionally exhibited intergranular fracture (see Fig. 8a). The large lamellar colonies invariably showed transgranular fracture, either translamellar, interlamellar or both in combination [7]. Fig. 8b highlights the details of translamellar crack growth. Intralamellar crack branching is evident (at the center of Fig. 8b and running into the plane of the photo). Secondary cracking produced a serrated appearance suggesting crystallographic slip/fracture.

Table III Specimens Selected for Fractographic Analysis

Alloy	Temp. (°C)	da/dn (in./cycle)	ΔK (ksi√in.)
47-XD	26	2×10^{-5}	10
47-XD	650	4×10^{-6}	10
45-XD	26	4×10^{-6}	10
47-5	26	4×10^{-6}	10

(a) **Fig. 8** Fracture surface of 47-XD at room temperature showing (a) translamellar fracture (upper left), intergranular fracture adjacent to single phase γ or β grain (center) and intralaminar fracture (lower right) and (b) details of translamellar fracture showing intralaminar crack branching into the photo plane.

At 650°C in the 47-XD alloy, the fracture path was primarily translamellar with regions of transgranular fracture evident where a number of fine grains occurred. Such a region is depicted in Fig. 9. Additionally, a number of TiB_2 needles are apparent in these grain boundaries.

Fractographic details of cast 45-XD appeared very similar to those observed in 47-XD at both ambient and elevated temperatures with predominantly translamellar fracture occurring, as shown in Fig. 10. Also shown is the presence of TiB_2 needles lying parallel to the crack propagation path within a α_2/γ lamellar colony. Intergranular fracture was again noted in fine grains adjacent to prior α grain boundaries.

Fig. 9 Fracture surface of 47-XD at 650°C showing slightly oxidized intergranular fracture in a region of fine grains.

Compared to the cast 47-XD specimens, the wrought 47-5 fully lamellar microstructure exhibited a much coarser fracture appearance. The

difference was due to the larger grain size in the wrought alloy. An apparent forging induced texture, parallel to the direction of crack propagation (perpendicular to the forging axis) was also noted. Intergranular fracture in areas of finer grains was much less common in the wrought fully lamellar microstructure. When observed, these finer grains were extremely fine and showed no evidence of lamellar structure. These grains may be grain boundary β or γ grains. Such grain boundary phases were observed previously in optical metallography (see Fig. 4).

Transgranular crack growth of the lamellar colonies predominated with interlamellar fracture resulting in a prominent "faceted" appearance (owing to the large γ/α_2 lamellar colonies). Intralamellar fracture could be observed on these facets producing a distinct texture with 120° symmetry (see Fig. 11). The 120° symmetry was composed of intralamellar fracture as detailed previously in Fig. 8.

Fig. 10 Fracture surface of 45-XD at 25°C showing extent of translamellar fracture with TiB_2 needles.

Fig. 11 Fracture surface of 47-5 at 25°C showing effect of texture in mixed translamellar and intralamellar fracture.

Conclusions

It has been concluded that alloy microstructure, boride morphology and chemistry for the alloys studied here have only a second order effect in determining fatigue crack growth threshold stress intensity. Even in the case where dynamic fracture toughness is elevated as in the 47-XD alloy at 650°C, threshold stress intensity was not significantly impacted. Through control of the α_2/γ colony lath size (through the introduction of TiB_2 precipitates in this case), similar properties in both cast Duplex, cast Nearly Fully Lamellar and wrought Fully Lamellar alloys can be achieved. Translamellar cracking is dominant with evidence of intergranular fracture occurring adjacent to duplex α grains or refined grains of α or β . Much further study is needed as different researchers are reporting differing effects of microstructure on crack growth. Some of these discrepancies may be attributable to the fact that a variety of alloys have been studied that were processed under a variety of conditions.

The relatively small range between K_{th} and K_{IC} leaves very little allowance for in service crack growth, therefore, design considerations will need to be made for operation well below K_{th} . In order to design and fabricate structurally reliable components, new failure criteria and design guides will need to be developed. This is particularly critical in the implementation of γ -TiAl, where low densities and high threshold stress intensities hold advantage in light weight and durability not attainable in conventional nickel base alloys.

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