EFFECTS OF CHROMIUM CONTENT ON FATIGUE CRACK GROWTH BEHAVIOR OF TI-48AL-XCR ALLOYS

Mohd Nasir Tamin [a], **Esah Hamzah**, **Ong Wei Rex**

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 UTM Skudai, Johor, Malaysia
[a] taminmn@fkm.utm.my

Abstract

Gamma TiAl alloys are candidate materials for aircraft structural applications due to their inherent high specific stiffness and strength. However, limited room-temperature ductility of these alloys calls for investigation on fatigue crack growth resistance. In this respect, a series of fatigue crack growth tests are conducted on pre-cracked M(T) specimens at constant load ratio of minimum to maximum stress, $R = 0.1$. All tests are performed at room temperature for baseline fatigue crack growth behavior. Effects of different chromium content on fatigue crack growth rates, da/dN and threshold stress intensity factor ranges, ΔK_{th} for Ti-48Al-xCr alloys (x = 0, 2, 4 and 8 at. %) are examined. Results show that fatigue crack growth behavior of these alloys displays a threshold growth stage followed by a power-law growth behavior until final fracture of the sample. The threshold ΔK_{th} ranges from 11 MPa√m for Ti-48Al to the lowest magnitude of 4.5 MPa√m for Ti-48Al-8Cr alloy. In the Paris-law crack growth region, da/dN ranges between 10^{-4} to 10^{-2} mm/cycle while the crack-tip driving force, ΔK varies from 11 to 35 MPa√m, respectively. The magnitude of ΔK at final fracture for Ti-48Al-xCr (x = 0, 2, 4 at. %) is about 34 MPa√m which approximate the fracture toughness of the alloys. Fracture toughness of Ti-48Al-8Cr alloy is much lower at 18 MPa√m. Threshold ΔK_{th} is linearly correlated with microstructure features of lamellar grain size and lath spacing. Dominant fatigue fracture mechanisms observed are crack deflection, stepped crack growth and formation of shear ligaments. These mechanisms are responsible for the observed torturous crack path and collectively improved crack growth resistance of Ti-48Al-xCr alloys.

Keywords: titanium aluminides; fatigue crack growth rates; threshold stress intensity factor range; fatigue fracture mechanisms

1. Introduction

The use of high strength-to-weight ratio materials in aerospace and automotive engine applications is essential for increased power output-to-fuel consumption and improved performance of the system. The moment of inertia of rotating components such as a turbine rotor primarily determines the performance of the system such that the use of lightweight material reduces both moment of inertia and transitional time. In this respect, the development of titanium aluminides alloys, TiAl offers promising alternative lightweight heat resistant materials to conventional heat resistant steels and superalloys.

Gamma titanium aluminides, γ-TiAl is an intermetallic alloy consisting of titanium and 40-55 at.% aluminum. Ti-48Al has been accepted as the best alloy among the two-phase alloys because of balanced mechanical properties [1]. It exhibits highest tensile strength, good ductility and excellent fatigue crack growth resistance compared to other alloys in the as-cast condition [2,3]. However, room temperature ductility, oxidation resistance and susceptibility to hydrogen pickup at high temperature are below the desired level [4]. Although the fatigue performance of titanium aluminides is unsatisfactory at near ambient temperatures, their high specific strength advantages are being exploited for aeroengine components based on enhanced fatigue crack growth behavior at elevated temperature approaching 1000^{o}C [5]. The limited room-temperature ductility of these alloys calls for investigation on fatigue crack growth resistance. Continuous improvement in fatigue crack growth resistance is being evaluated through optimization of microstructures and mechanical properties to meet the demands from aerospace and automotive industries [6].

Fatigue crack growth resistance is an important mechanical property for γ-TiAl alloys applications as structural materials. Previous studies have indicated that the mechanical properties of γ-TiAl alloys are strongly dependent on the microstructure of the alloys. Three typical microstructures of γ-TiAl alloys are lamellar, equiaxed-γ and duplex microstructures. Of these microstructures, lamellar displayed excellent fatigue crack growth resistance [7]. The microstructures in TiAl alloys can be varied by heat treatment or by addition of β-stabilizing elements such as chromium, niobium, and vanadium. The addition of chromium to the binary TiAl alloys has been reported to improve room temperature ductility, high temperature oxidation resistance and some mechanical properties of the alloys [8]. These excellent alloying effects make chromium a candidate β-stabilizing element for further investigation. Considerable improvement in ductility and toughness can be achieved in the two-phase alloys consisting of γ-TiAl and α_2-Ti_3Al phases.

This paper presents and discusses the effects of different chromium contents in γ-TiAl alloys on fatigue crack growth behavior at room temperature. Microstructure variables such as lamellar grain size and lamellar lath spacing are correlated with fatigue crack growth parameters. Fractographic analysis of the fractured surfaces revealed the dominant fracture mechanisms responsible for the observed fatigue crack growth resistance of the alloys.

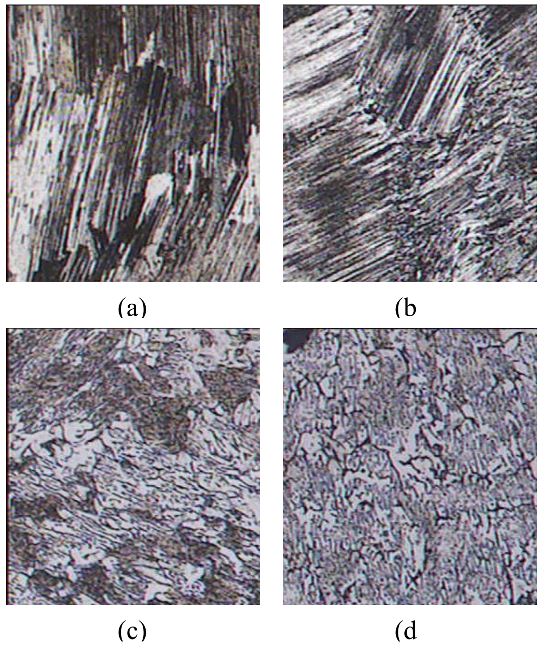

Fig. 1. Microstructures of as-cast Ti-48Al alloys with different chromium contents: (a) none (b) 2 at.% (c) 4 at.% and (d) 8 at.%.

2. Materials and Experimental Procedures

The materials investigated in this study are Ti-48Al-xCr (x = 0, 2, 4, 8 at.%) alloys produced by plasma-melt casting technique to form 2 kg-button each. The cast buttons are examined in the as-received condition. Table 1 shows the chemical composition of each type of sample.

Table 1. Chemical composition of various Ti-48Al-xCr alloys in at.%

Samples	Ti	Al	Cr
Ti-48Al	52.64	47.34	-
Ti-48Al-2Cr	51.32	46.45	2.23
Ti-48Al-4Cr	46.79	48.66	4.55
Ti-48Al-8Cr	46.67	45.39	7.94

Microstructures of all samples with different chromium contents are compared in Fig. 1. Ti-48Al and Ti-48Al-2Cr alloys exhibit a near-fully lamellar microstructure consisting of primarily lamellar colonies with alternating laths of α_2-Ti_3Al phase (hexagonal $D0_{19}$ structure) and γ-TiAl phase ($L1_0$ structure) along with some single γ grains. The coarse and inhomogeneous columnar grains are directionally formed during solidification from the shell towards the core of the as-cast buttons. The near-lamellar microstructure of Ti-48Al-4Cr alloy consists of fine γ-phase and β-phase (BCC structure). Greater amount of β-phase is observed with the addition of 8 at.% chromium. The chromium content in β-phase (12.85 at%) is higher than that in γ-phase (5.39 at%) which has also been reported earlier [9]. The β grains are irregular in shape and sandwiched with γ grains at the grain boundaries of the near-lamellar microstructure.

The lamellar grain sizes and lath spacing for each type of Ti-48Al samples, measured using an image analyzer are correlated with the chromium content of the alloy as shown in Fig. 2. Results indicate that the average lamellar grain diameters decrease from 16.45 to 6.33 μm with increasing chromium content. Similar trend of decreasing average lamellar spacings from 3.733 to 0.870 μm was recorded when chromium content was increased up to 8 at.% in Ti-48Al alloys. The presence of ternary element of chromium in Ti-48Al resulted in finer γ and α_2 plates in the lamellar structures. The decrease in lamellar grains sizes and lath spacing have indicated improvement in the mechanical properties of the alloys [10].

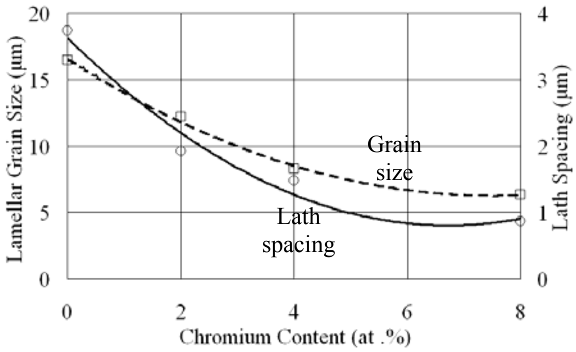

Fig. 2. Effects of chromium content on microstructure features of Ti-48Al alloys

A series of fatigue crack growth tests are performed on center-cracked, M(T) specimens of width, W = 30 mm and thickness, B = 2 mm. The specimens are wire-cut so that the surface-plane of the specimen is oriented parallel to the central axis of the as-cast button. Upon fatigue loading, crack will propagate in the direction perpendicular to the radial cooling direction of the as-cast button. The surface of the specimens is mechanically ground and polished to mirror-like finish to aid in optical measuring of crack lengths. Each specimen is pre-cracked to an initial crack length, $2a_0$ of approximately 2 mm. All tests are performed at room temperature on Instron 100 kN servo-hydraulic dynamic testing machine with stress range, $\Delta\sigma$ = 100 MPa, load ratio of minimum to maximum stress, R = 0.1 and loading frequency of 10 Hz. Test procedures adheres to ASTM-E647 standard practices for fatigue crack growth tests.

3. Results and Discussion

The effects of chromium content on fatigue crack growth response of Ti-48Al alloys are presented and discussed in terms of the measured crack growth rates and identified crack growth mechanisms.

3.1. Fatigue crack growth behavior

Fatigue crack growth behavior of Ti-48Al-xCr alloys examined in this study is compared in Fig. 3 in terms of normalized crack lengths, $2a/2a_0$ versus loading cycles, N. The crack grows at a slow rate at the beginning of each test and accelerates as the crack length increases after accumulating larger number of cycles. This is consistent with the increase in stress intensity factor ranges as the crack lengthens. The last point on each curve represents the final fracture of the specimen during the fatigue crack growth testing. It is noted that Ti-48Al-2Cr alloy endured the longest life at 40,445 cycles while Ti-48Al-8Cr the shortest at 14,073 cycles. In all samples, catastrophic fracture occurred after the final crack lengths reached larger than 3.5 times their initial lengths. The excellent fatigue crack growth behavior displayed by Ti-48Al-2Cr alloy indicates optimized chromium content at 2 at.% for toughness enhancement. Additional chromium (4 and 8 at.%) introduces the hard β phase that reduce room temperature ductility and toughness of the alloy.

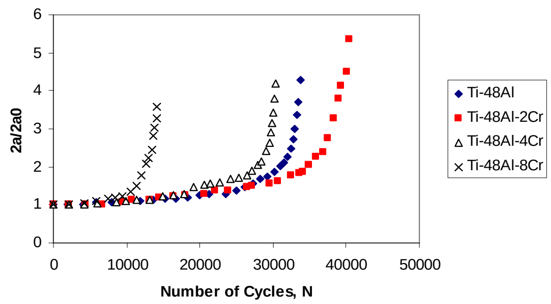

Fig. 3. Fatigue crack growth behavior of Ti-48Al-xCr alloys

Fig. 4 compares the fatigue crack growth rates behavior of the alloys. The fatigue crack growth rate, da/dN is plotted against the applied stress intensity factor range, ΔK. Results show that fatigue crack growth behavior of T-48Al alloys displays a threshold growth stage followed by a power-law growth behavior until final fracture of the specimens. This two-stage crack growth rate response of cast Ti-48Al alloys has also been observed in earlier studies [eg. 11,12]. The threshold ΔK_{th} is the level of stress intensity factor range below which the existing crack in the structure will not grow. The variation of ΔK_{th} with chromium content in Ti-48Al-xCr alloys investigated is listed in Table 2. The threshold ΔK_{th} ranges from 4.5 MPa√m for Ti-48Al-8Cr to the highest magnitude of 11 MPa√m for Ti-48Al alloy. In the power-law growth region, the crack growth rate is commonly represented by Paris equation [13]. In this region, da/dN ranges between 10^{-4} to 10^{-2} mm/cycle while the crack-tip driving force, ΔK varies from 11 to 35 MPa√m, respectively for Ti-48Al-xCr (x = 0, 2, 4 at. %). The magnitude of ΔK at final fracture is about 34 MPa√m which approximate the fracture toughness of the alloys. Fracture toughness of Ti-48Al-8Cr alloy is much lower at 18 MPa√m.

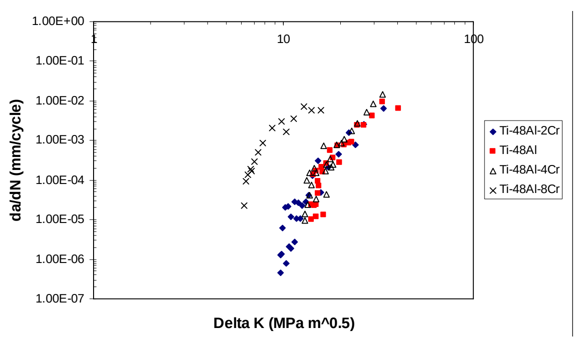

Fig. 4. Fatigue crack growth rates of Ti-48Al-xCr alloys

Table 2. Variation of threshold stress intensity factor range, ΔK_{th} with chromium content in Ti-48Al-xCr alloys

Samples (at. %)	ΔK_{th} (MPa√m)
Ti-48Al	11.0
Ti-48Al-2Cr	8.0
Ti-48Al-4Cr	6.0
Ti-48Al-8Cr	4.5

The measured threshold ΔK_{th} levels for Ti-48Al alloys examined in this study are correlated with microstructure features, namely lamellar grain sizes and lath spacing as shown in Fig. 5. Results indicate that threshold ΔK_{th} is linearly correlated with lamellar grain size and lath spacing for Ti-48Al-xCr alloys with chromium content up to 8 at.%. The threshold ΔK_{th} decreases with an increase in chromium content as shown in Table 2. The addition of 4 to 8 at% chromium leads to precipitation of β phase and fine microstructure that, in-turn lowers ΔK_{th} level. Low ΔK_{th} is undesirable as it may induce growth of existing crack-like defects at low operating load level.

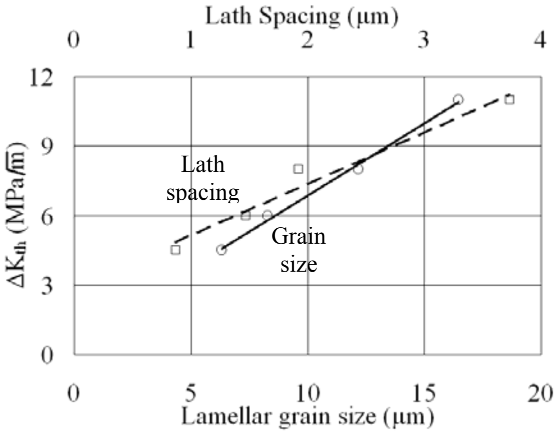

Fig. 5. Correlations between ΔK_{th} and microstructure features for Ti-48Al alloys with different chromium content

3.2. Fatigue crack growth mechanisms

A typical fatigue crack path in Ti-48Al-2Cr alloy specimen under the tensile Mode-I loading is shown in Fig. 6. However, complex stress states prevail in the vicinity of a structural crack tip. The local stress at the crack tip (1) initiates interlamellar crack by slip along lamellar lath or along weak α_2-γ interface of the lamellar structure [14,15]. The interlamellar crack then propagates along lamellar lath and retards at the grain boundary due to the adjacent colony with different lamellar orientation. With additional load cycles, the interlamellar crack is deflected and continues to grow along the grain boundary that is oriented at a low angle to the horizontal plane [16]. This crack deflection (2) mechanism caused the interlamellar crack to change its direction at specific angle with respect to the loading plane during the crack propagation process. Other dominant fatigue crack growth mechanisms observed are stepped crack growth (3) and the formation of shear ligament (4), as identified in Fig. 6. These mechanisms contribute to improved fatigue crack growth resistance of the alloy as reflected by the torturous crack path. It is worth noting that the addition of chromium does not alter the fatigue crack growth mechanisms of the Ti-48Al alloys.

4. Conclusions

The addition of chromium up to 8 at.% to the composition of γ-Ti-48Al alloys has demonstrated significant effects on microstructure and the corresponding fatigue crack growth behavior:

- Systematic addition of chromium (2 – 8 at.%) to Ti-48Al alloys reduces lamellar grain size and lath spacing.
- Largest number of fatigue cycles are endured by Ti-48Al-2Cr alloy with the corresponding $2a/2a_0 = 5.5$ at fracture.

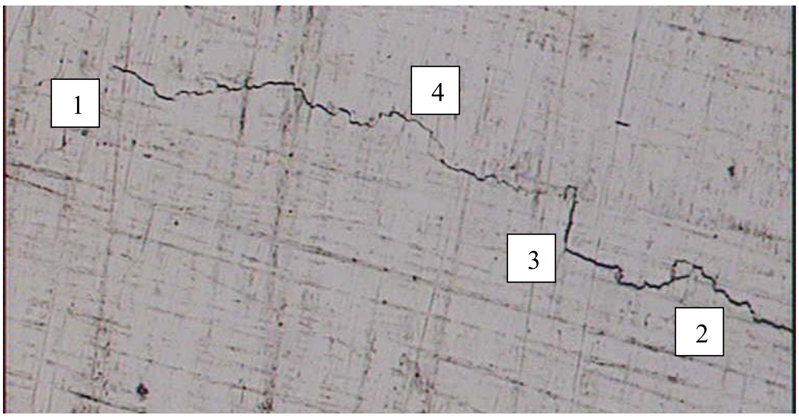

Fig. 6. Optical micrograph of fatigue crack path in Ti-48Al-2Cr. Loading direction is vertical and the crack propagated from right to left. (200X mag)

- Threshold ΔK_{th} linearly correlates with microstructure features of lamellar grain size and lath spacing. ΔK_{th} increases with increasing lamellar grain sizes and lath spacings, but decreases with an increase in the chromium content.
- Dominant fatigue crack growth mechanisms identified are crack deflection, stepped crack growth and the formation of shear ligament.

Acknowledgment

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