INFLUENCE OF ENVIRONMENT, LOADING FREQUENCY AND TEMPERATURE ON FATIGUE CRACK GROWTH MECHANISMS IN TITANIUM LAMELLAR MICROSTRUCTURES

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ABSTRACT

High temperature fatigue crack growth experiments were carried out on Ti6242 alloy with large colony size in both air and vacuum environment. The alloy was heat treated to provide two different lamella size; fine and coarse. Tests were conducted at two temperatures, 520°C and 590°C, using two loading frequencies; 10 Hz and 0.05 Hz in air and 0.05 Hz in vacuum. All tests were performed at a stress ratio of 0.1. This study shows that at 520°C/air, the fatigue crack growth rate is not significantly influenced by changes in the lamella size microstructure. For 0.05 Hz / low ΔK, however, the fatigue crack growth rate is higher in the fine lamellar microstructure and is accompanied with the appearance of a plateau. In air environment, the fatigue process is predominantly controlled by one single mechanism associated with transcolony fracture and formation of quasi-cleavage facets. In Vacuum conditions, the crack growth rate is not greatly influenced by temperature or lamella size. In comparing the fatigue crack growth rate in air and vacuum, the vacuum results are generally lower than the corresponding ones in air within the ΔK= 18-25 MPa√m. Above this level, the CGR data in both air and vacuum coincides thus indicating the role of environment in the low ΔK growth stage. A general hypothesis explaining the crack growth mechanisms in both air and vacuum is made in this study on the basis of scanning electron microscopic observations of the crack growth path in relation to the lamella direction as a function of loading frequency, temperature, lamella size and test environment.

1 INTRODUCTION

The current study explores the crack tip damage process in α/β Ti lamellar microstructures and its interaction with the loading frequency and temperature in both air and vacuum. For that purpose, fatigue crack growth tests are performed at elevated temperatures on a commercial α/β titanium alloy, Ti-6Al-2Sn-4Zr-2Mo-0.1Si (Ti6242) with three lamellar microstructures varying in their lamella size and colony size. All tests are carried out at a typical service temperature, 520°C, and at higher temperature, 595°C, using two different loading frequencies; 0.05 and 10 Hz. All vacuum tests were performed at 0.05 Hz. The first part of the paper presents the experimental procedure used for the fatigue crack growth testing. This includes the description of the heat treatment route conducted on the microstructures of this study. The results of the fatigue tests obtained in terms of crack growth rates and associated fracture mechanisms are then presented and commented through SEM examinations. The last part discusses the significance of loading frequency, temperature, microstructure and environment in the controlling crack growth process and its relationship with the crack tip slip transmission at α/β interfaces.

2 EXPERIMENTAL PROCEDURE

The material used in this study was forged at 30°C above the β transus (995°C). Its chemical composition is: Ti-balance, Al-6.000, Sn-1.940, Zr-4.095, Mo-2.045, Si-0.115, Fe-0.031, C-0.009, O-0.011 (in weight %). A series of solutioning treatments was carried out in order to change the size of the features of this microstructure. The resulting microstructures will be referred to as fine lamellar and coarse lamellar lamellar microstructures. The average dimension of α platelets, in each of these microstructures is 0.7 and 5.9 µm, respectively. The average size of the β lamellae is found to be similar in all produced microstructures, and equal to 0.2 µm. Fatigue crack growth (FCG) experiments were conducted using compact tension specimens made of the microstructures presented above. The crack growth was measured using optical measurements made on the two sides of the test specimen. In addition, the crack growth was monitored using the potential difference method. All FCG tests were conducted on automated servo-hydraulic material testing systems. Heating of the specimens in air was achieved using a clamshell furnace in which the specimen temperature is controlled by two thermocouples spot-welded on two opposite corners of the top and bottom surfaces of the specimen. Heating in vacuum was established by quartz lamps with the vacuum reaching a level of 7×10^{-6} torr using a turbo molecular pump. Tests in both air and vacuum were conducted at two temperatures, 520°C and 595°C. All tests were performed with a constant load ratio $R = 0.1$. Scanning electron microscopy was used to examine the fracture surface of test specimen specimens.

3 RESULTS

The FCGR experiments performed at 520°C (air) show that the presence of a 300s hold time at peak stress has no influence on these microstructures. Moreover, it was shown that the microstructure has little influence on the FCGR at ΔK values higher than 30 MPa√m. Differences were observed at 0.05Hz below this ΔK level. The FCGR of the fine lamellar microstructure was found to be independent of ΔK in the early stage of propagation, see Fig 1(a). Comparing both air and vacuum results for the 0.05 Hz, the plateaue observed in air conditions below 30 MPa√m disappears under vacuum testing. Results of the two test conditions coincide for higher ΔK values indicating the absence of environmental effects. Influence of microstructure in vacuum shows that that the microstructure has no influence on the crack growth rates.

At 595°C, it is observed that the effects of loading frequency and hold time on the FCGR remain, to a large extent, similar to those reported at 520°C. No noticeable changes in the crack closure levels were detected at 595°C as a function of ΔK. One could discern, however, a slight increase in the overall FCGR at 595°C. Furthermore, the microstructure is not influential on the FCGR, even at the early stage of propagation, where differences were detected at 520°C. In vacuum, the FCGR at 595°C is found to be moderately higher than that correspond to 520°C, see Fig. 1(b). The slope of the growth curves indicates that the increase is related to fatigue mechanisms rather than time-dependent effects.

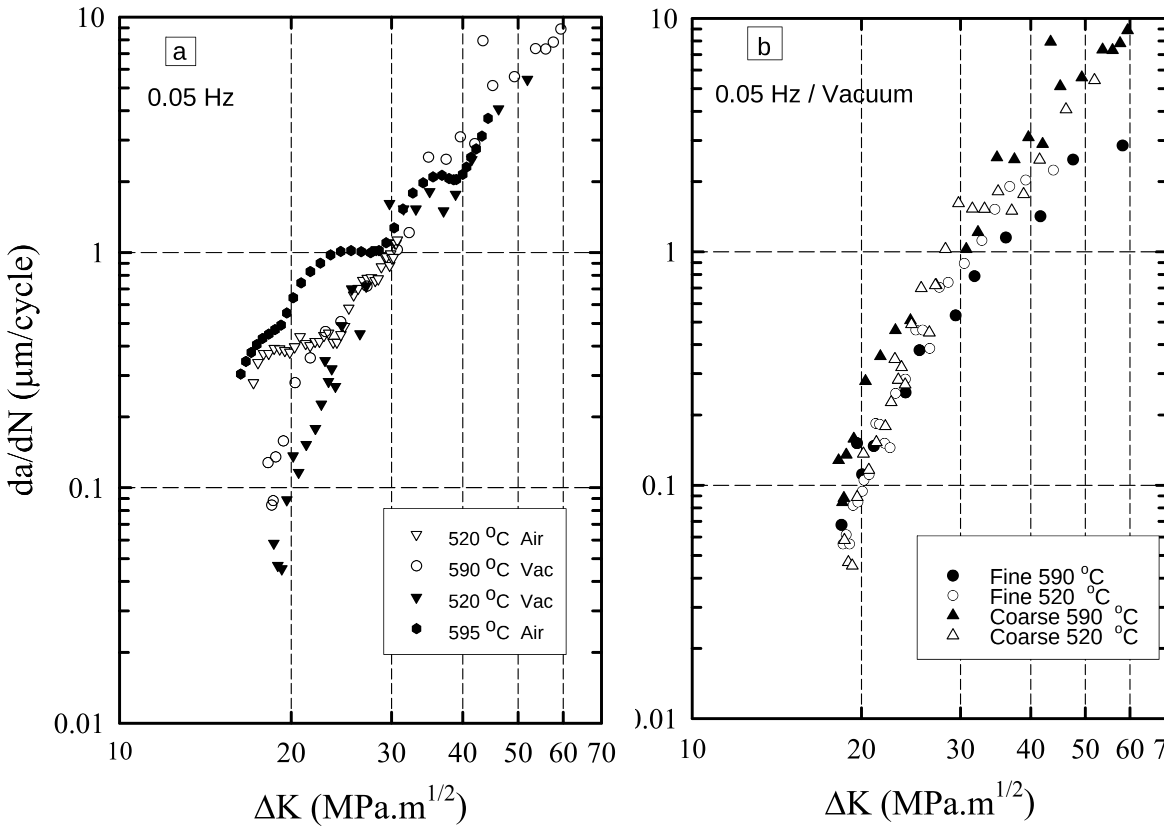

Figure 1: Fatigue Crack Growth Rate Results in both Air and Vacuum Tests

In order to detect a preferential direction for quasi-cleavage with respect to the colony orientation, the angle between the planar crack path and the long axis direction of fractured colonies has been measured. These results show that the crack growth directions are concentrated along near-0^o and near-90^o angles. These two angles of primary interest correspond to either parallel or transverse crack paths, respectively, with respect to the long axis direction of the α platelets. It is important to note that in the case of parallel-to-lamella crack path, the failure process occurs within the α phase with no apparent α/β interface sliding. At 10 Hz and 520^{o}C, an equal tendency for parallel and transverse cracking exists. On the other hand, a decrease of the loading frequency to 0.05 Hz leads to a significant reduction for transverse crack paths, and predominance for parallel crack paths. At 595^{o}C, both low and high loading frequencies exhibit near-0^o and near-90^o crack paths, suggesting that the crack path selectivity observed at 520^{o}C as a function of the loading frequency is almost absent at this temperature. Vacuum results show that the crack orientation is temperature dependent, particularly in the low Δk range. At 520^{o}C the percentage of parallel and transverse crack directions are 33% and 15%, respectively. At 595^{o}C these ratios become 16% for parallel direction and 41% for the transverse direction. These ratios are relevant to the increase in the crack growth rate observed at the higher temperature level in vacuum.

4 DISCUSSION

The crack growth and fracture surface results presented above will be discussed here on the basis of shear activity associated with transverse and parallel crack path configurations. While assuming perfect Burgers' relationships between α-Ti and β-Ti platelets, the c-axis [0001] of the α phase is aligned with the β platelets long axis orientation and one prism direction of the α phase coincides with one <111> direction of the β phase [1,2]. Consequently, shear activities leading to the parallel crack path configuration may be attributed to <a>-slip in $\left(01\bar{1}0\right)$ prism plane or, eventually, to various pyramidial <c+a>-slips. On the other hand, shear leading to the transverse crack path which could not coincide with $\left(01\bar{1}0\right)$ prism slip, may be relevant to shear activities along (0001) basal slip, $\left(10\bar{1}0\right)$ prism slip or, eventually, pyramidial slip. Moreover, the possibility of slip occurring along any of these prism or basal directions is generally determined by the corresponding critical resolved shear stress (CRSS). The work of Williams et al [3] on single crystals of Ti-Al alloy containing up to 6.6% Al, has shown that the CRSS of prism planes is generally lower than that of basal planes. The differences in the CRSS values between these two slip systems, however, decrease as the temperature increases. Furthermore, in a study of the slip modes in titanium, Churchman [4] presented a model on the effect of small concentrations of oxygen on the slip systems in alpha titanium. The model predicts that interstitial oxygen atoms interfere with <a> type glide more severely in the basal (0001) and the prismatic slip plane $\{10\bar{1}0\}$ than in the pyramidal slip planes $\{10\bar{1}1\}$. For a random solid solution, as obtained under conditions of stress-enhanced crack tip oxygen diffusion, Churchman's model predicts that interstitial atoms interfere with the dislocation motion in the basal and prism planes, but only one half of the interstitial atoms interfere with the pyramidal planes. Thus, the CRSS, which was lowest on prism and basal, is increased by oxygen, such that, once reaching large oxygen concentration, slip can become comparable or even preferred in the pyramidal planes.

Based on this discussion and results given above, three mechanisms are suggested as the controlling fracture processes as a function of temperature, loading frequency, microstructure for driving forces above 30 MPa√m. At these levels, the influence of environment is absent. These mechanisms are represented schematically in Fig. 2 which is divided into four mechanisms. Mechanisms I and II correspond to mechanisms observed at the low temperature level. Mechanism I emphasizes high loading frequency conditions while mechanism II is relevant to low frequencies. The role of α/β interfaces on limiting the slip in $\mathbf{a_2}$ prism direction is the controlling deformation mechanism in mechanism II. At high loading frequency, the role of the interface is limited due to the confinement of the deformation, which is observed to be restricted to a few platelets ahead of the crack tip [5]. Mechanisms III and IV in Fig. 17 correspond to the deformation mechanisms at temperatures near 595°C. In mechanism III, the increase of temperature, as previously discussed, makes slip along basal planes easier and in turn, promotes cracking paths perpendicular to the lamellae. In this regard, it has been reported that the substructure of Ti6242, which shows creep behavior at 565°C is dominated by glide of <a>-type cusped dislocations on both basal and prism planes [6]. Moreover, possibilities of dislocation pile-up at the interface are reduced, allowing wavy slip patterns to operate. As a result, the slip anisotropy envisaged at a lower temperature is likely to be inhibited at 595°C.

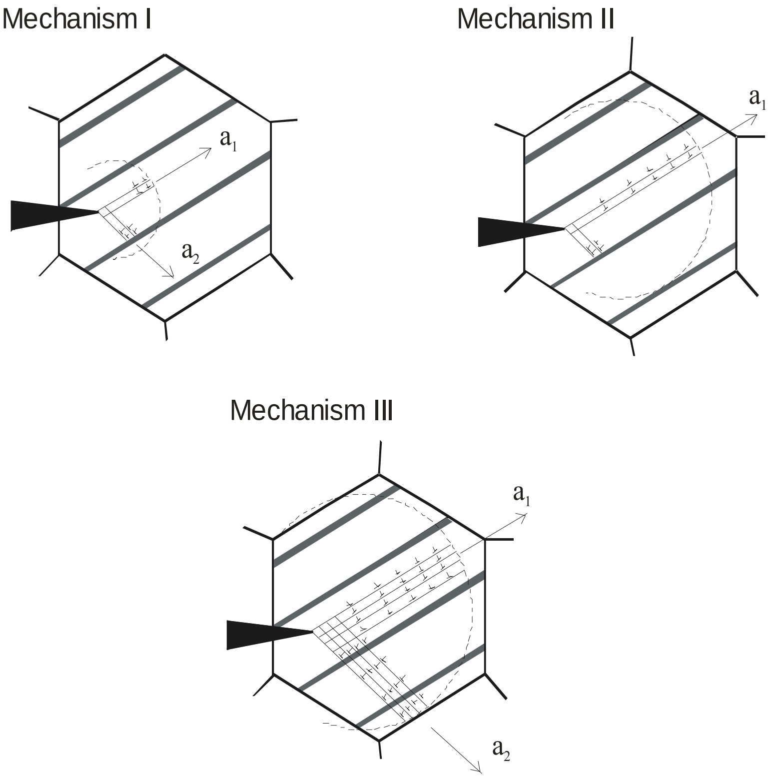

Figure 2: Proposed Fatigue Crack Growth Mechanisms as a Function of Temperature and Loading Frequency for driving force > 30 MPa√m

5 CONCLUSIONS

Fatigue crack growth experiments were carried out on three fully lamellar microstructures of Ti6242 alloy at two temperatures, 520^{o}C and 595^{o}C for the loading frequencies of 10 Hz and 0.05 Hz. The latter frequency was examined in both air and vacuum environment. All the tests were performed at a stress ratio of 0.1. Major results of this study can be summarized as follows:

- At 520^{o}C (air), the FGCR at 10 Hz is not significantly influenced by changes in the microstructure. This behavior also exists for the 0.05 Hz at ΔK higher than 30 MPa√m. At lower ΔK, the FCGR is higher in the fine lamellar microstructure and is accompanied with the appearance of a plateau.

- At 595^{o}C (air), while the general level of the FCGR is higher than that of 520^{o}C, effects of the loading frequency remains approximately similar to that at the lower temperature level. Unlike results at 520^{o}C, the FCGR at low ΔK is not influenced by variations in lamellar microstructure. An increase in the crack growth rate occurs at ΔK higher than 31 MPa√m.

-For vacuum tests, the crack growth rate not very sensitive to varaiations in lamella size, however, in the range ΔK= 18-25 MPa√m, the growth rate shows small increases with temperature. Above this ΔK level the growth rate is almost similar for all vacuum tests. In comparing the FCGR in air and vacuum, the vacuum results are generally lower than the ones in air within the ΔK= 18-25 MPa√m. Above this level, the CGR data in both air and vacuum coincides. This result indicates that environmental effects are the key components in crack acceleration in the early growth stage, while above ΔK= 25 MPa√m, the crack growth process is environment independent.

- All tests in air and vacuum show that the fatigue process is predominantly controlled by one single mechanism related to transcolony fracture associated with the formation of quasi-cleavage facets, which are oriented along heavily sheared slip bands.

- The fatigue crack growth results and the associated fracture behavior as obtained in this study are rationalized in terms of the crack tip slip process. It is proposed that the reduction of a_2 prism slip with the decrease in the loading frequency plays a significant role in the decrease of perpendicular-to-lamellae crack paths at 520^{o}C. In addition, the decrease of the loading frequency results in diminishing the homogeneity and density of the slip at the crack tip, which tends to reduce interactions between adjacent slip planes. The lack of cross slip causes a decrease of CRSS for macroscopic plastic flow and softening in both a_1 and a_2 prism directions, which leads to higher crack growth rates. At 595^{o}C, the increase of temperature reduces the anisotropy of slip transmission at the α/β interfaces and further promotes cracking on of the basal plane along a direction perpendicular to the α/β interface.

6 REFERENCES

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