INVESTIGATION OF THE ABNORMAL NEAR-THRESHOLD FATIGUE CRACK PROPAGATION ON A Ti6246 ALLOY.

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ABSTRACT: *This paper deals with a study on a perplexing phenomenon which has been recently reported on several titanium alloys which were found not to exhibit a threshold in ambient air at room temperature or 120°C when tests are run at high mean stress levels and very low stress intensity factor ranges. In such conditions, these materials revealed a stationary regime with a constant growth rate. This paper is devoted to the determination of the factors influencing the occurrence of this phenomenon, including mean stress level, test frequency (35 Hz and 3.5 Hz), temperature (room temperature, 150°C and 500°C) and environment through comparative tests performed in air and in high vacuum.*

INTRODUCTION

The knowledge of the threshold stress intensity below which fatigue cracks do not propagate is of importance in assessing the significance of various crack like defects which can be introduced by manufacturing processes or which may arise as a result of service operation. At near threshold stress intensities, fatigue crack growth rates have been found to be sensitive to mean stress, microstructure, environment…[1,2]. Recently, a perplexing phenomenon has been reported in which several titanium alloys [3,4] were found not to exhibit a threshold in ambient air at room temperature or 120°C. Under loading conditions gathering a low stress intensity factor range ΔK and a K_{max} higher than a critical level but substantially lower than the fracture toughness, the crack can grow at a constant rate up to the failure. Following the initial observation by Sarrazin-Baudoux et al. of such behavior in a Ti6246 [5], the present study was undertaken on the same alloy to investigate the influence of several factors including mean stress, temperature, frequency and environment (air and high vacuum), on the fatigue crack growth behavior in the near-threshold area, the aim being to get a better understanding of this phenomenon and to precise the conditions for its occurrence.

EXPERIMENTALS

The tested titanium alloy is an α-β Ti6246 type (6Al-2Sn-4Zr-6Mo) which contains 75% of α grains. It displays a Widmanstätten structure as shown in the figure 1, consisting of intermeshing colonies of α platelets contained in large prior β grains (300 µm), the size of the actual α grains being not exceeding 50 µm. The mechanical properties at room temperature are given in Table 1.Fatigue crack growth experiments were carried out on Compact Tension (CT) specimens (10 mm thick and 40 mm wide) using a servo-hydraulic machine equipped with an environmental chamber and a furnace allowing testing in ambient air, high vacuum (10^{-4} Pa) at temperatures ranging up to 500°C.

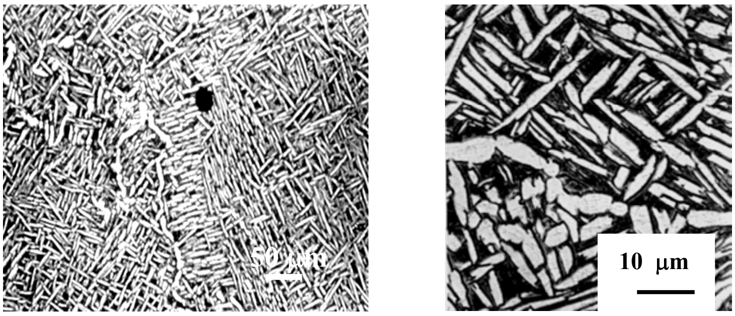


Figure 1: Illustration of the Ti6246 microstructure

Table 1 : Mechanical properties of Ti6246 at room temperature

Chemical Composition	σ_y (MPa)	σ_u (MPa)	A %	E (GPa)	K_{1C} (Mpa√m).
5.68 Al,1.98 Sn, 3.96 Zr, 6.25 Mo	985	1098	10.2	122	75

The crack propagation rate was determined using two methods. The first one consists in a shedding procedure of the load which was decreased by steps of 8% down to the threshold, the average crack advance being of

0.1 mm. The second one consists in a computer controlled procedure with a progressive decreasing of the stress intensity factor range ΔK such as $Cg=(1/\Delta K).(d\Delta K/da)=0.1\ mm^{-1}$, in accordance with ASTM Test Method for Measurements of Fatigue Crack Growth Rates (E 647-88). K_{max}-constant tests were conducted in conditions where K_{min} was higher than the stress intensity level for crack closure so as to eliminate closure in all the explored range of growth rate. The absence of crack closure was checked out by mean of a capacitive detector using the upset compliance technique as initially proposed by Kikukawa and al [6].

RESULTS AND DISCUSSION

Critical stress level for a no-threshold behavior at room temperature

Crack growth data for tests conducted at room temperature in ambient air at five increasing K_{max} levels are shown in figure 2. For stress intensity factor ranges, ΔK, higher than 3 MPa√m, the crack growth rate da/dN appears independent on K_{max} and all data fall within the same scatter band. At lower ΔK ranges and for K_{max} levels lower than 46 MPa√m, a threshold is obtained with a value close to 2 MPa√m. But above K_{max} = 52MPa√m, the abnormal near-threshold behavior is observed, and the growth rate becomes independent on the ΔK and is stabilized at some 10^{-6} mm/cycle. In accordance to available literature, these results confirm the existence in ambient air of the abnormal near-threshold behavior detected by Marcy [3] and Larsen and co-authors [4].

Influence of environment.

In the figure 3, data in air and in vacuum are compared for two K_{max} levels of 46-47 MPa√m and 57 MPa√m. As in air, the abnormal behavior is encountered in high vacuum at K_{max} of 57 MPa√m supporting that it should be related to an intrinsic governing mechanism. It can be noticed that the crack propagation rate, as well at K_{max} of 57 MPa√m in the steady regime as at 46 MPa√m when thresholds are obtained, appears to be slightly faster in air (about two to three times) than in vacuum, suggesting some assistance environment to the cracking process.

Influence of test frequency

Crack growth data for tests conducted at K_{max}=57 MPa√m using two different frequencies of 35Hz and 3.5Hz are shown in figures 4a and 4b.

From the figure 4a, it can be seen that test frequency has no influence on the fatigue propagation at ΔK ranges higher than 3 MPa√m where crack growth rates are quite similar for the two tested frequencies. At lower ΔK, the steady regime is detected at both frequencies. The growth rate at 3.5 Hz expressed in mm/cycle appears to be nearly one order of magnitude higher than that at 35Hz but is quite similar in term of da/dt illustrated in the figure 4b. In this last figure, the curves can be divided in three main domains according to the ΔK range:

- at low ΔK, the propagation mechanism is time dependent and corresponds to a creep-like process with a growth rate described in term of da/dt;
- at ΔK > 3 MPa√m, the crack growth rate is ΔK-controlled and corresponds to a fatigue process described in term of da/dN;
- at intermediate ΔK (1 to 3 MPa√m), both fatigue-controlled and creep-controlled mechanisms contribute to crack advance and the growth rate can not be rationalized in term of da/dN nor in term of da/dt.

The cold creep regime seems operative when the size of the cyclic plastic zone $r_{yc} = 0.3\ (\Delta K/2\sigma_y)^2$, where σ_y is the yield stress, becomes equal or smaller than the size of microstructural elements as the thickness of the α lamellae (about 1 μm). In the studied Ti6246, such conditions for the localization of the cyclic deformation are encountered for ΔK< 2.2 MPa√m. For the test run at 35Hz, this ΔK range is attained at a growth rate of $3\ 10^{-6}$ mm/cycle which corresponds to a steady cold creep rate of 10^{-4} mm/s. When the test is run at 3.5Hz, this steady state corresponds to $3\ 10^{-5}$ mm/cycle and is attained at a much higher ΔK range than at 35 Hz, i.e. close to 6 MPa√m. At such stress intensity level, conditions for localization of the deformation are not completed and the growth rate is still decreasing when lowering ΔK. When ΔK is equal or smaller than 2.2 MPa√m, the steady regime is reached after a slight acceleration which explains the shape of the curve with a dip in the growth rate (figure 4a).

Influence of temperature

Crack growth data of tests performed at room temperature, 150°C and 500°C in air at K_{max} = 57 MPa√m are plotted in the figure 5.

A very striking result is the observation of a threshold at 150°C. This suggests an important change in the microscopic behavior of the material particularly in the dislocation slip mechanisms between room temperature and 150°C. A parallel analysis can be made with the so called “dwell effect”

[7] commonly observed on several Ti alloys and which also has been shown to disappear at comparable temperature.

At 500°C, the no-threshold behavior occurs again but with a steady rate of about 3 to 4x10^{-9} mm/cycle which is one order of magnitude lower than that at room temperature. As for metallic alloys, such behavior at elevated temperature can be attributed to a combination of fatigue and creep contributions which is consistent with cracked surfaces (figure 5b) which exhibit both interlamellar and transgranular ductile areas with flat dimples. This aspect is different of that for cold creep at room temperature (figure 5a) characterized by crystallographic cleavage-like facets in the α phase surrounding by ductile and highly deformed β phase. At 150°C, the near threshold fatigue cracked surface (figure 5c) presents a typical transgranular fatigue morphology with a flat aspect poorly marked by the microstructure in contrast to the cold creep fracture surface. These observations suggest that the reduction in the resistance of the material against sustained load at room temperature can result from a damaging process which develops ahead of the crack tip and consists in the rupture of α platelets along crystallographic facets. Then, the rupture of the material would result from a coalescence of these damaged areas together with the ductile rupture of the remaining β phase surrounding the laths [8].

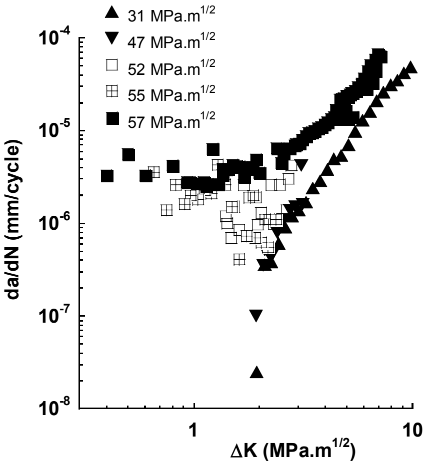


Figure 2: Propagation curves in ambient air at room temperature for different K_{max} levels.

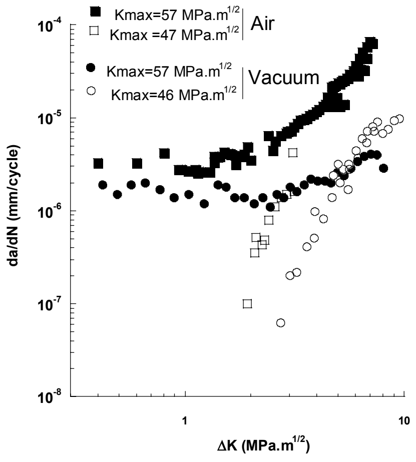
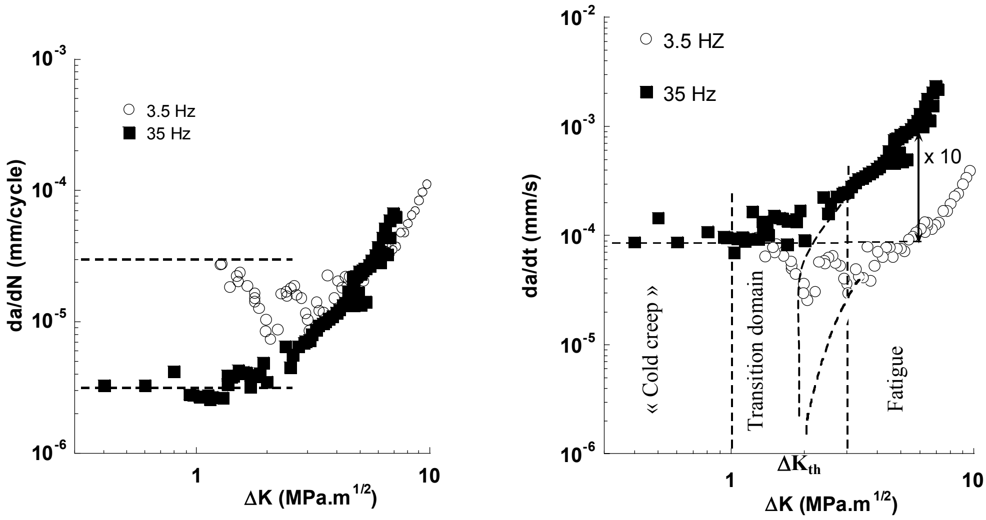


Figure 3: Comparison of crack propagation curves in air and high vacuum at room temperature.



(a) **(b)**

Figure 4: Influence of frequency on the fatigue crack propagation at room temperature in ambient air: (a) da/dN vs ΔK, (b) da/dt vs ΔK.

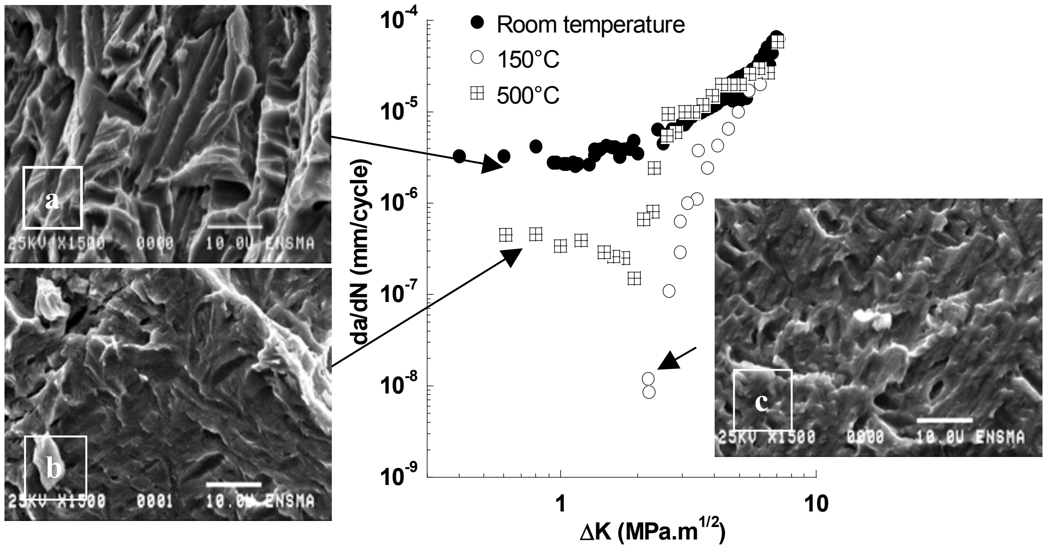


Figure 5: Influence of temperature on crack propagation rate for tests run at $K_{max} = 57$ MPa√m.

DISCUSSION

Cold-creep at room temperature has been more precisely investigated by performing K-constant test without cycling between two steps of decreasing procedure of the ΔK during the threshold test. The sustained stress intensity factor was equal to the K_{max} constant level applied during the previous fatigue step. The figure 6 represents the crack advance versus the time after various decreasing ΔK levels at K_{max} of 57 MPa√m. For each ΔK range, the crack growth exhibits a delay τ(s) during which there is no progression of the crack, followed by a steady propagation at a constant growth rate da/dt. In figure 7, τ(s)□ is plotted with respect to the ΔK range of the fatigue precycling. It can be seen that $\tau(s) = 0$ for $\Delta K<2$ MPa√m, this critical range is the same as that calculated for the localization of the cyclic plastic zone at the scale of the microstructural elements. In conclusion, the delay seems to correspond to the time required to induce damage by sustained loading in the cyclic plastic zone at the crack tip. Thus, the duration of the delay might be related to the size of this cyclic plastic zone. At high ΔK range, the delay is long and the sustained loading damage has no time to develop during the fatigue test while at very low ΔK, the cyclic plastic zone is very small (<1 μm) and the sustained loading damage can develop quite instantaneously. For intermediate ΔK, both sustained loading and cyclic loading damage are cumulating in the transition domain as illustrated in the figure 4b.

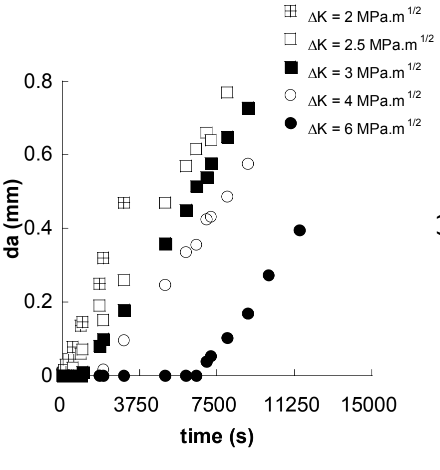


Figure 6: Crack advance under sustained loading at K_{max} of 57 MPa√m versus the time after cycling at several ΔK.

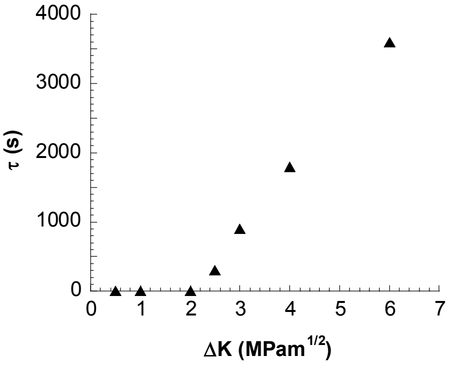


Figure 7: Delay for sustained load cracking at K_{max} of 57 MPa√m versus ΔK range of previous cyclic loading.

CONCLUSIONS

The disappearance of the fatigue-threshold on the studied high strength Ti6246 Titanium alloy, has been related to a cold-creep process at room temperature.

- This phenomenon results from the superimposition of a constant K_{max} level of about 70% of the fracture toughness and of a cyclic loading at a low ΔK range (< 2 MPa√m). It can be related to similar cold creep process on several titanium alloys which has been evoked in the literature to explain delayed cracking under sustained loading, and has been generally attributed to a result of hydrogen embrittlement [8].
- The no-threshold effect is observed at room temperature as well in high vacuum as in ambient air which supports an intrinsic origin.
- At $K_{max} = 57$ MPa√m, a conventional fatigue threshold is obtained at 150°C and high temperature creep fatigue-interaction prevails at 500°C.
- Tests performed at 35Hz and 3.5Hz confirm that the crack propagation mechanism in the low ΔK range is time dependent.

REFERENCES

1. Davidson, D. and Suresh, S., (1984) *Fatigue Crack Growth Threshold Concept*, TMS AIME Pub., Warendale, PA,.
2. Newman, J. C. and Piascik, R. S., (2000) *Fatigue Crack Growth threshold, Endurance Limits, and Design, ASTM STP 1372*, ASTM Pub., West Conshohocken, PA,.
3. Marci, G., (1996) In : *Fatigue 96*, pp.493-498, G. Lütjering et al. Eds. Pergamon Press, **1**.
4. M. Lang, G.A. Hartman, and J.M. Larsen, (1998) *Scripta Mat.*,**12**, 1803.
5. Sarrazin-Baudoux, C., Chabanne, Y., and Petit, J., (2000) *ASTM STP 1372*, pp. 341-360, J.C. Newman, Jr. And R.S. Piasick, Eds., Philadelphia.
6. Kikukawa, M., Jono, M. and Mikami, S., (1982) *Journal of the Society on Materials Science Japan,* **31**, 438.
7. Evans W.J., Gostelow C.R. (1979) *Met. Transactions*, **10A**, 1837.
8. C. Sarrazin-Baudoux, Y. Chabanne, J. Petit and J.M. Olive, 2000 *ECF 13*, *Fracture Mechanics: Applications and Challenges.*