MEAN STRESS, TEMPERATURE AND ENVIRONMENT INFLUENCES ON NEAR-THRESHOLD FATIGUE CRACK BEHAVIOR OF TI6246.

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ABSTRACT

The present paper is addressing a study of the cracking behavior of a Ti6246 alloy under cyclic loading superimposed to different levels of mean stress, specially focused on the near threshold fatigue crack propagation regime, and to possible coupled effects of fatigue and creep. Tests were conducted at room temperature,150°C and 500°C. The effect of environment is analyzed through comparative tests performed in air and in high vacuum. The conditions for the occurrence of an abnormal behavior consisting in the disappearance of the threshold for sufficiently high K_{max} level, are discussed in comparison with similar behavior described in the literature on several other Ti alloys. The possible involved mechanisms are discussed through SEM and AFM observations.

INTRODUCTION

The existence of a threshold for fatigue crack growth is of considerable practical importance since many engineering components are subjected to low amplitude cyclic loading. Then, a knowledge of the threshold stress intensity below which fatigue cracks do not propagate is clearly 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. Recently a perplexing near-threshold behavior has been reported in the literature for several Titanium alloys when the K_{max}-constant test method [1,2] is used. This experimental procedure is valuable when one wants to determine the threshold value of the effective stress intensity factor range in condition eliminating the contribution of crack closure. The maximum stress intensity factor, K_{max}, is kept constant, while the minimum, K_{min}, is gradually increased until the threshold is reached. But when the value is sufficiently high and the fatigue amplitude, ΔK, becomes sufficiently small, different Ti alloys, IMI 834, IMI 685, Ti 6Al-6V-2Sn [1] and Ti-6Al-6V-2Sn, IMI685, Ti-6Al-2Sn-4Zr-6Mo [2] are found not to exhibit an effective threshold. It is noticeable that this kind of effect has not been detected at room temperature on Ti-6Al-4V [1], Nickel-base super alloy IN100, 7475 T7351 Al alloy [2] and has been up to now only observed on several Titanium alloys.

In the context of another study of the fatigue crack growth behavior of Titanium alloys at elevated temperature, a no-threshold effect has been detected by Sarrazin-Baudoux et al [3] on a Ti6246 alloy tested at 500°C in moist environments evoking a possible interaction between fatigue, creep and stress corrosion cracking.

This paper presents new results of a detailed investigation of the influence of mean stress on the fatigue crack growth behavior of a Ti6246 alloy in the near-threshold area. The influence of factors as the temperature and the nature of the gaseous environment has been explored, and the search for the understanding of the involved micromechanism is supported by SEM and AFM micrographic observations. The analysis of the results referred to previous studies on the influence of a gaseous environment on fatigue crack propagation [5].

MATERIAL AND EXPERIMENTAL PROCEDURES

The Ti6246 alloy used is β-forged at 950°C. The heat treatment consists of 930°C for two hours, followed by water quenching, aged at 900°C for one hour and air cooled, held at 595°C for a total aging time of eight hours and air cooled. The microstructure as illustrated in Figure 1 consists in 75% of α grains and displays Widmanstätten intermeshing colonies of α platelets (size being not exceeding 50 μm) contained in large prior β grains (300 μm).

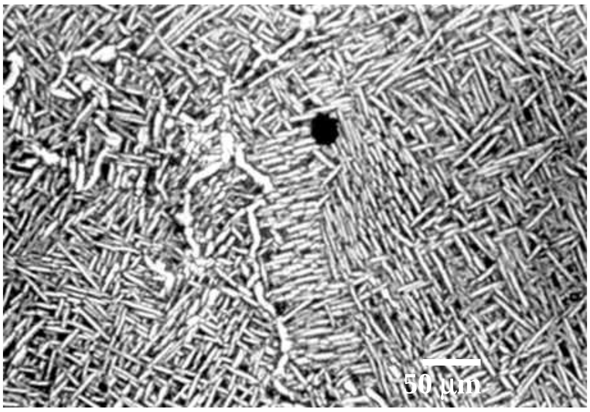


Figure 1: Microstructure of the Ti6246 alloy

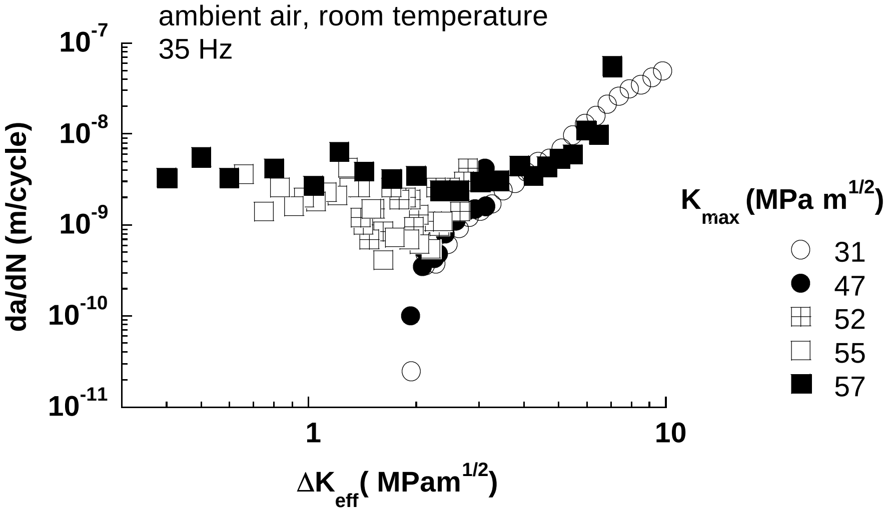
Fatigue crack growth experiments are carried out on Compact Tension (CT) specimens (10 mm thick and 40 mm wide) using a servo-hydraulic machine equipped with an environmental chamber and a furnace allowing testing in ambient air, high vacuum (10^{-4} Pa) and controlled atmospheres such as humidified argon with controlled partial pressure of water vapor, at temperatures ranging up to 500°C. Crack lengths are tracked using a DC (electrical) potential drop technique. Precracking for all specimens is carried out at room temperature at R = 0.1. In accordance with ASTM recommendations (standard E647, 1986), the crack propagation rate is determined using a shedding procedure of the load which is decreased by steps of 8% down to the threshold, the average crack advance being of 0.1mm. For tests performed at increasing ΔK after threshold, the load is progressively increased by step of 3 to 5 %. The specimens are submitted to sinusoidal loading at frequencies varying from 35 Hz to 10^{-3} Hz at variable R (Kmax-constant tests), which means in conditions where K_{min} is 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 being checked out.

INFLUENCE OF THE MEAN STRESS ON THE FCP BEHAVIOR

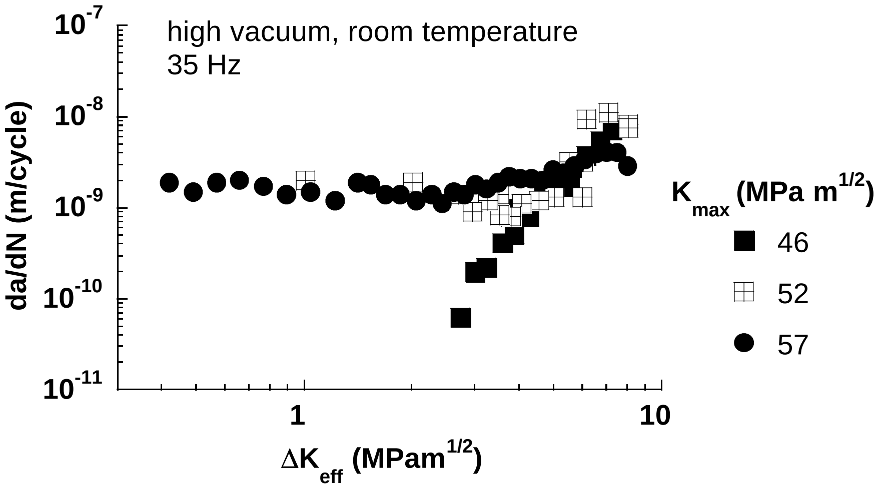
Room temperature

Crack growth data for tests conducted at room temperature in ambient air and in high vacuum are given in Figure 2 [3]. Five K_{max} levels were tested in air and three levels in high vacuum. For stress intensity factor ranges, ΔK, higher than 3 MPa√m in air (Figure 2a) and 5 MPa√m in vacuum (Figure 2b), 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 47 MPa√m, a threshold is obtained with a value close to 2 MPa√m in air and

3 MPa√m in vacuum. But above K_{max} = 52 MPa√m, an abnormal near-threshold behavior is observed, and, in both environments, the growth rate becomes independent on ΔK and lays around some 10^{-9} m/cycle in air and $2x10^{-10}$ m/cycle in vacuum. These results confirm the existence in ambient air of an abnormal near-threshold behavior as recently detected by Marci [1] and Larsen and co-authors [2]. In the figure 3 are compared data exhibiting this abnormal behavior in different Ti alloys. It is of importance to notice the similitude of the response of the different materials but also the difference in the K_{max} levels at which this phenomenon is observed. Furthermore, data in high vacuum also demonstrate its existence in an inert environment, supporting that this phenomenon is associated to an intrinsic mechanism.



(a)



(b)

Figure 2: Fatigue crack propagation curves in air (a) and in high vacuum (b) at room temperature for different K_{max} levels (35 Hz).

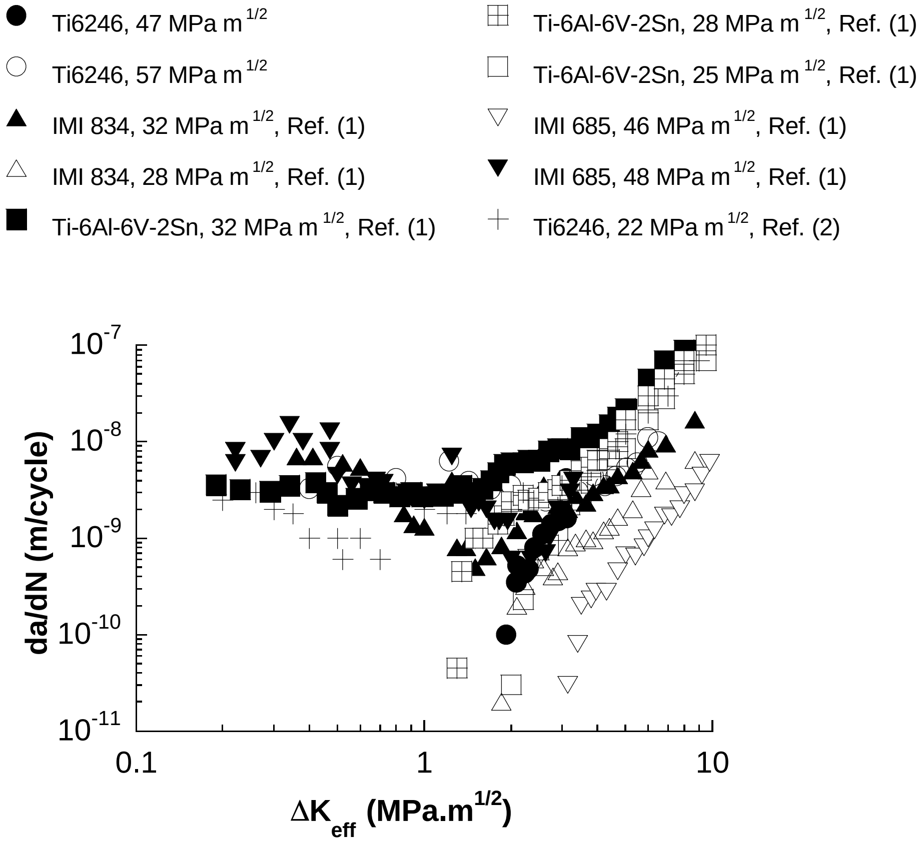


Figure 3 : Compilation of experiments demonstrating the existence of no-threshold behavior in various Ti alloys called the Marci effect at room or moderate temperature

Influence of temperature

Results in air at room temperature are compared in Figure 4 to that obtained at 150°C and 500°C at a K_{max} level of 57 MPa√m.

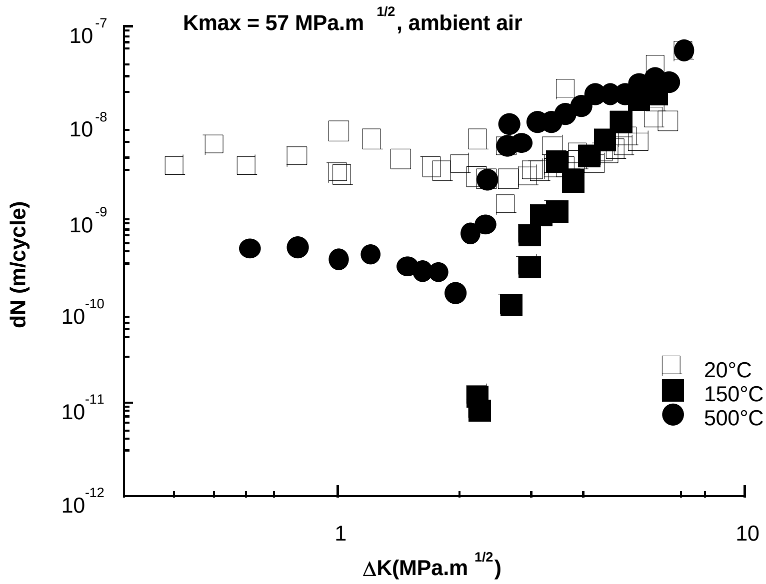


Figure 4 : Comparison of propagation curves obtained in air, at room temperature, 150°C and 500°C for K_{max} = 57 MPa√m

The no-threshold behavior is not observed at 150°C. Indeed more extensive experiments are required to confirm if this is a total disappearance or not. However this suggests an important change in the microscopic behavior of the material particularly in the dislocation slip mechanisms. A parallel analysis can be made with the so called “dwell effect “ [5] commonly observed on several Ti alloys and which also has been shown to disappear at comparable temperature.
At 500°C the no-threshold behavior is detected in air at K_{max} of 57 MPa√m with a steady crack growth ranging about 3 to $4x10^{-9}$ m/cycle which is much lower than the rate measured at room temperature as well in air as in high vacuum in the same loading conditions. Such behavior at elevated temperature can be analyzed in terms of a combination of fatigue and creep contributions. So the abnormal behavior is typically what is observed at room temperature and seems to disappear at some 150°C. Such behavior suggests the existence of some “cold creep” contribution in addition to fatigue when the applied mean stress is sufficiently high. Similar cold creep process has been evoked in the literature to explain another abnormal behavior of several Titanium alloys subjected to delayed cracking under sustained loading [6,7].

DISCUSSION

As evoked above, the operating crack growth mechanisms to obtain the no-threshold regime correspond to the combination of a static load and a cyclic one as well at room temperature as at 500°C but the governing processes appear to be different. These assumptions are reinforced by the microfractographic observations made on cracked surfaces.
Cracked surfaces obtained in the creep fatigue regime at 500°C and K_{max} of 57 MPa√m are illustrated in the figure 5. The morphology looks like a ductile fracture both interlamellar and transgranular with the presence of flat dimples. This aspect is quite different of that observed at room temperature in the same loading conditions (fig. 6a) with a very rough and tortuous crack path corresponding to a mixed aspect of the propagation with some large intergranular areas at the ex β grains (fig. 6b) and transgranular areas with crystallographic cleavage-like facets (fig. 6c) in the α phase and a ductile rupture of the β phase.
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.
To try to find some evidences of a such damage process, observations were undertaken on the surface specimen close to the fracture surface. An SEM illustration is given in the figure 7a. The specimen is tilted at an angle of 45° and the α laths are revealed by etching performed before the cracking test. Such SEM magnification is not sufficient to reveal any damage within the α lath. AFM observations of the same area of the specimen surface are illustrated in the figure 7b. At such magnification the presence of small parallel slip bands crossing the α platelets is detected. At higher magnification, (figure 8), a more detailed examination gives evidence of the development of microcracks along some of these bands which can be kinked or stepped with the linking of two neighboring bands. In figure 7b, shear bands parallel to the main crack are shown to develop by coalescence of the above mentioned microcracks existing in the a platelets ahead at the crack tip. The reason for the development of such damage process can be the same as that governing the cracking of Ti alloys under sustained loading [6, 7]. This is generally attributed to a result of hydrogen embrittlement with basal slip system [8], hydrogen being provided as well from internal hydrogen or external species such as absorbed water vapor.

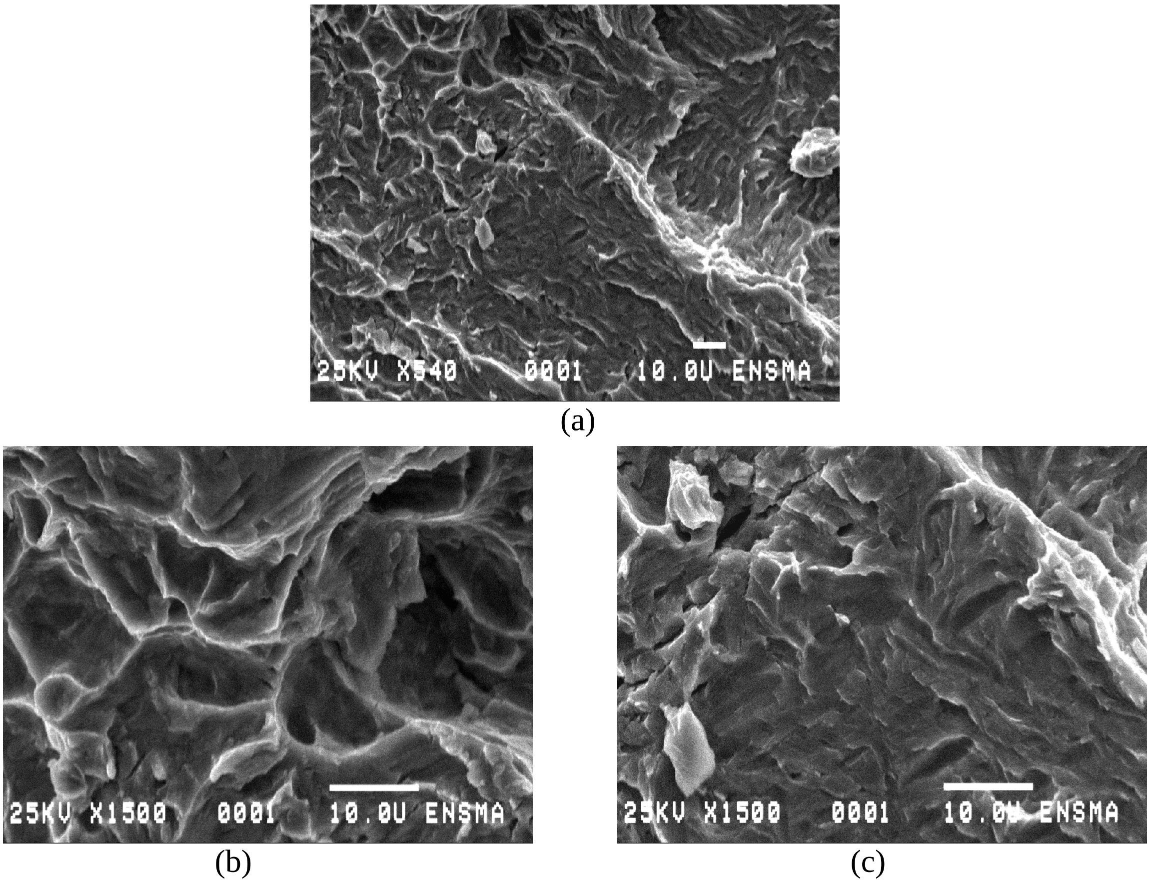


Figure 5 : Cracked surface obtained in the creep-fatigue regime in air, at 500°C (K_{max} = 57 MPa√m)

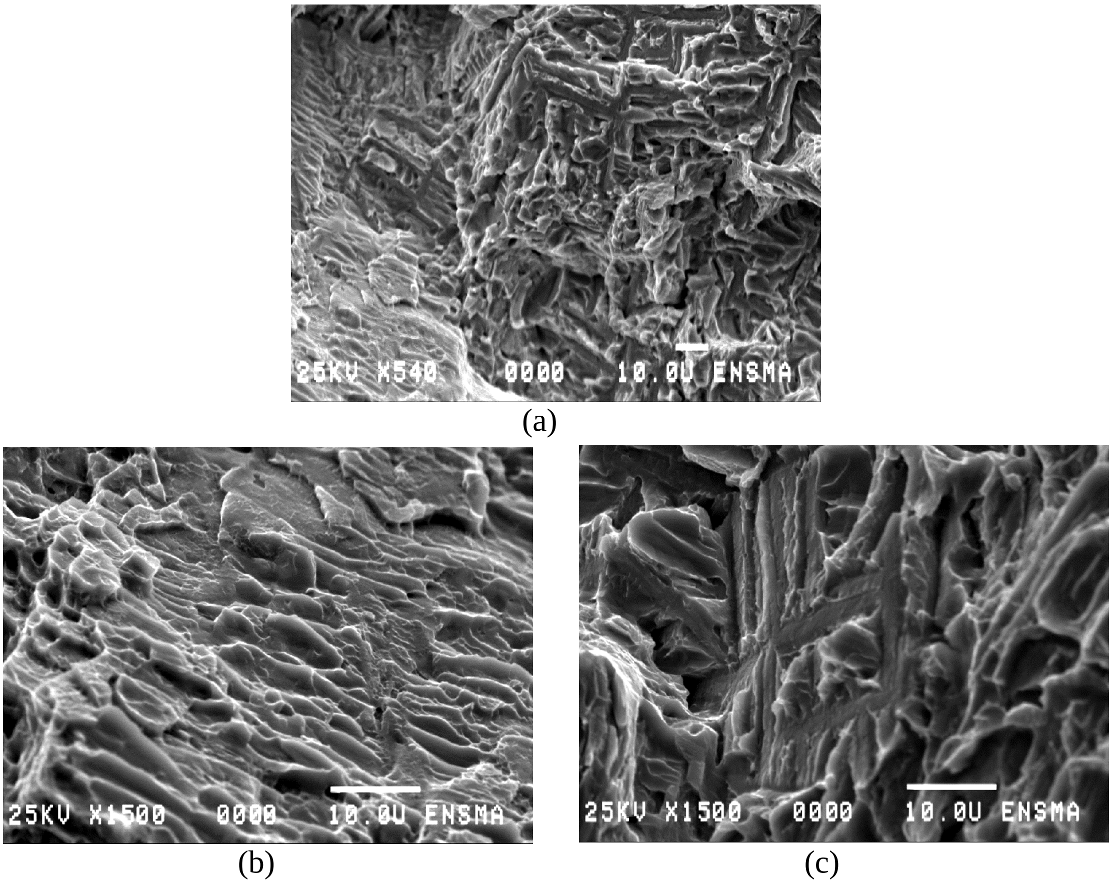
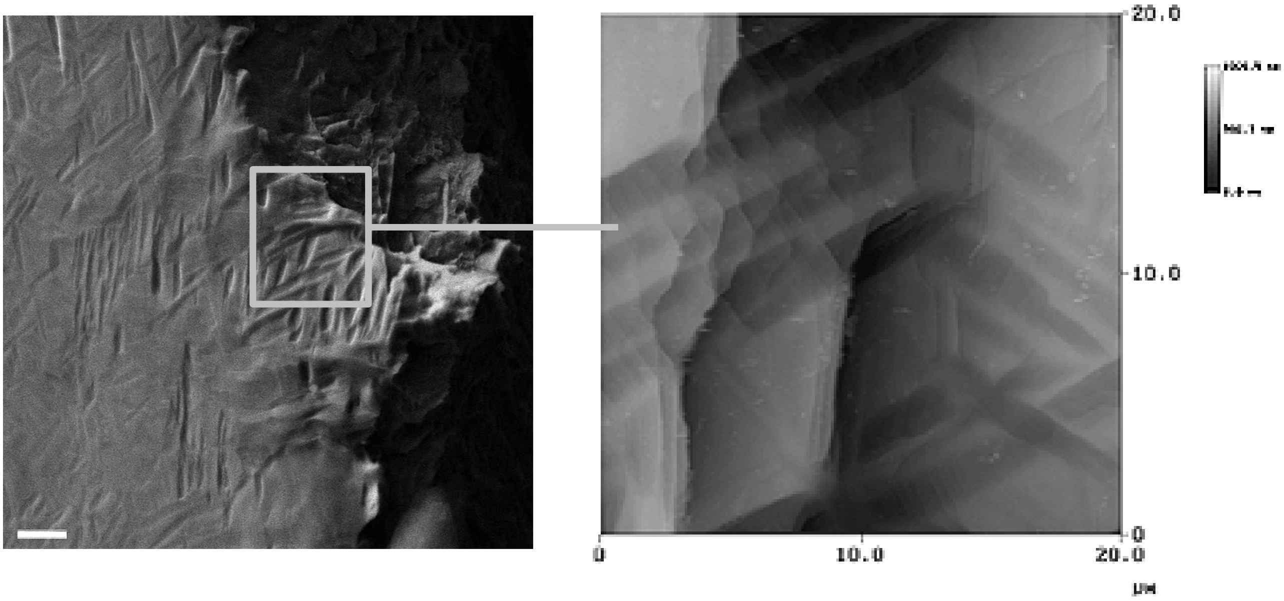


Figure 6 : Cracked surface obtained in the creep-fatigue regime in air, at RT (K_{max} = 57 MPa√m)



(a) (b)

Figure 7: Illustration of the specimen surface, (a) SEM view, (b) AFM view

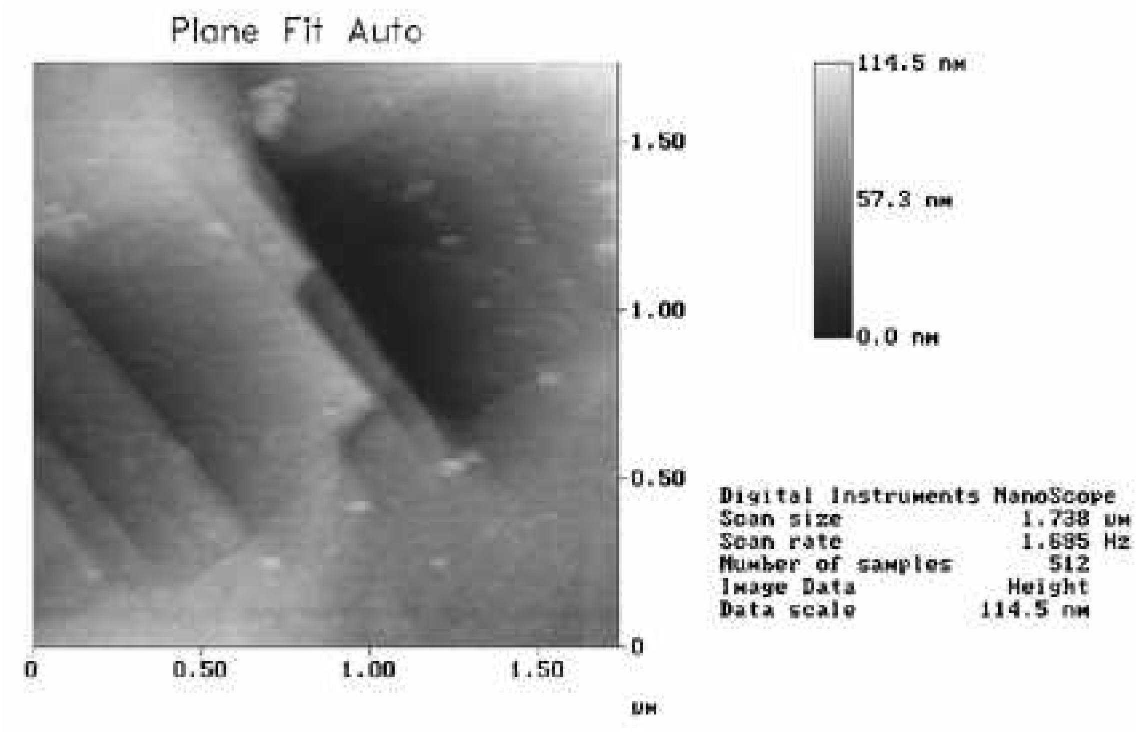


Figure 8: AFM observation at high magnification of slip bands and microcracks in α platelets

CONCLUSIONS

The following conclusions can be drawn :

A near-threshold abnormal behavior consisting in the disappearance of the threshold and resulting in a constant crack growth rate independent on ΔK is observed at room temperature as well in high vacuum as in ambient air, when two conditions are fulfilled : i) K_{max} higher than a critical level about 52 MPa√m which means around 70% of the fracture toughness, ii) superposition of cycling loading at ΔK lower than some 3 MPa√m. This phenomenon is also observed at 500°C and the rate of the steady propagation is about ten time slower than at room temperature.

The no-threshold behavior, is attributed to a creep contribution in addition to cyclic fatigue. A conventional creep process is observed at 500°C while a “cold creep” process typical of Ti alloys is operative at room temperature and seems to disappear at 150°C. Such cold creep is related to the development of damage ahead of the crack tip consisting in microcracking of α platelets along localized slip bands which could be hydrogen assisted.

On a practical side a conservative evaluation of the critical size of a crack or defect must be done on the basis of a critical stress intensity level substantially lower than the conventional fracture toughness.

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