FATIGUE CRACK PROPAGATION IN TA6V AT ELEVATED TEMPERATURE

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ABSTRACT

Fatigue crack propagation behavior of Ti-6Al-4V alloy elaborated in three different microstructures has been studied at 300°C. The specific influence of air environment is investigated by comparing the crack propagation in air, vacuum and humidified nitrogen. The role of the microstructure is concurently explored considering mainly the influence of primary α volume fraction and grain size. The resistance against crack growth at 300°C is shown strongly affected by environment and microstructure mainly in the low rate range ($<10^{-8}$ m/cycle). Different propagation regimes are identified and discussed on the basis of microfractographic and EBSP observations.

KEYWORDS

Fatigue, Crack Propagation, Titanium alloys, Microstructure, Temperature, Environment.

INTRODUCTION

Titanium alloys are particularly suited to aeronautical applications which have to face two primary problems, i.e. weight saving and increased operation temperatures in turbine engines. So, investigation of damage tolerance of Ti alloys are needed for components experiencing high cycle fatigue, a typical example being engine discs.

Recently the effect of R ratio has been investigated in ambient air (1-3) showing an increase in the growth rates with increasing temperatures in Ti-8Al-1Mo-1V alloy. After closure correction (2) a temperature effect is still observed at 260°C compared to room temperature (RT). So as to analyse the respective influence of environment and microstructure, this paper deals, on one hand, with experiments performed in vacuum on a TA6V alloy to provide reference data in inert environmental conditions, and, on the other hand, with experiments conducted in air or controlled atmosphere (Nitrogen + water vapour) to get information on the influence of the atmospheric environment.

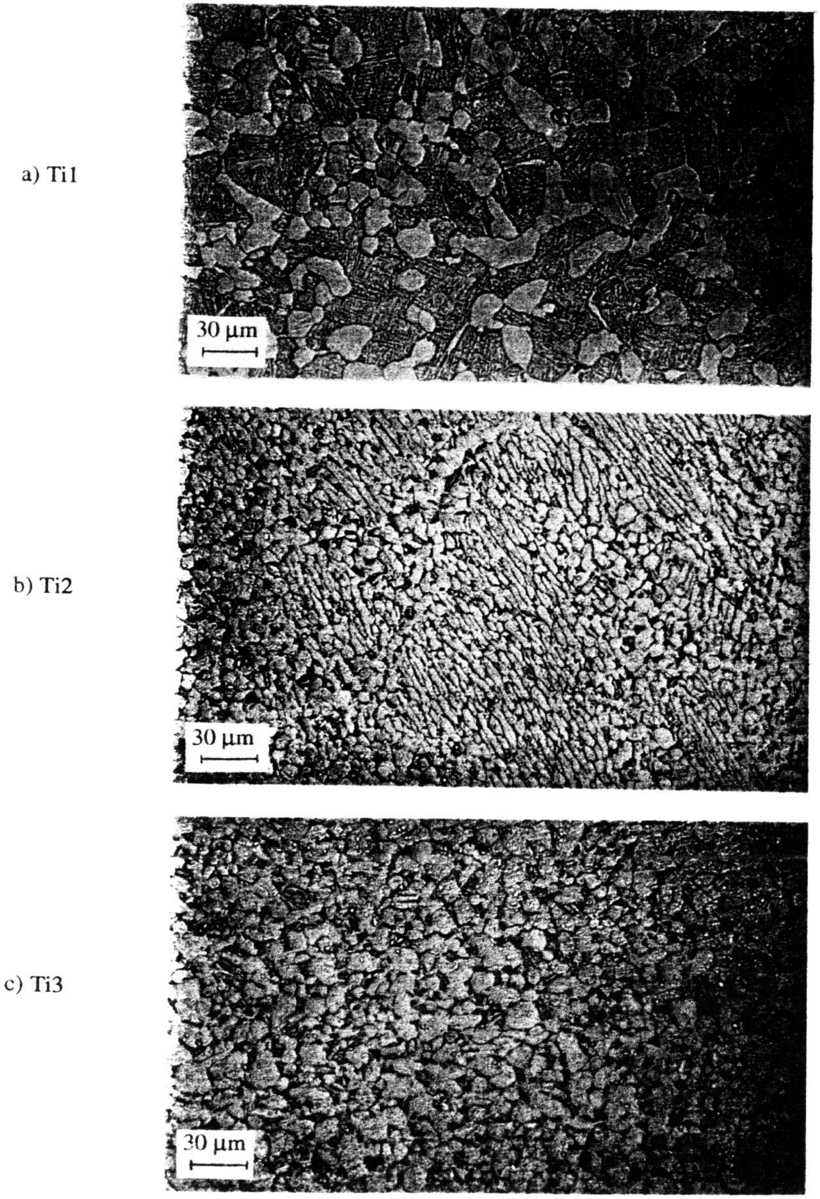


Figure 1 : Illustration of the three microstructures

EXPERIMENTAL DETAILS

The material used was a forged Ti-6Al-4V alloy (wt % 6.27 Al, 3.86 V, 0.12 Fe, 0.18 O_2). After forging, three different microstructures were obtained (table I).

Table I : Alloys properties

Nuances	heating (1h)	Water quenched	aging (2h)	Air cooled	σ_y (MPa)	σ_y (MPa)	E(GPa)	A %	Z %
Ti1	955°C		700°C		993	1038	122	16	45
Ti2	965°C		705°C		975	1035	123	16	47
Ti3	-		705°C		1000	1050	123,5	14	36

Ti1 presents a bimodal microstructure consisting of 35 % of equiaxed primary α grains having an average size of 20 µm (fig. 1a).

Ti2 has a heterogeneous microstructure consisting of 80 % globular α_p (8 µm in diameter) and colonies of α_p platelets (100 µm wide and 8 µm thick) all outlined by β phase (fig. 1b).

Ti3 has a homogeneous microstructure consisting of 80 % of globular α_p (10 µm in diameter) outlined by β phase (fig. 1c).

Crack propagation tests were carried out on a servo-hydraulic testing machine equipped with an environmental chamber containing a furnace providing temperatures up to 475°C in high vacuum ($< 5\times10^{-4}$ Pa). CT specimens were 10 mm thick and 32 mm wide. The test frequency was of 35 Hz and the load ratio R of 0.1 or variable (for constant K_{max} testing).

Crack advance was monitored using a potential drop system, and near-threshold propagation was explored using a load shedding procedure for test performed at decreasing ΔK in accordance with ASTM recommandations. Observations of the cracked surface were performed using a Scanning Electronic Microscope and an Electron Back Scattering Pattern system.

Influence of microstructure

Figures 2 and 3 illustrate respectively the nominal crack propagation behavior of the three nuances of TA6V at room temperature (RT) and at 300°C.

At RT there is only very little influence of microstructure. At 300°C, the bimodal structure gives the poorest resistance against crack propagation, data for the two other alloys being quite similar. In addition, for each alloy, an acceleration of crack growth is systematically observed at 300°C with a plateau phenomenon at about 10^{-8}m/cycle which appears to be a critical rate below which temperature has a very much larger influence.

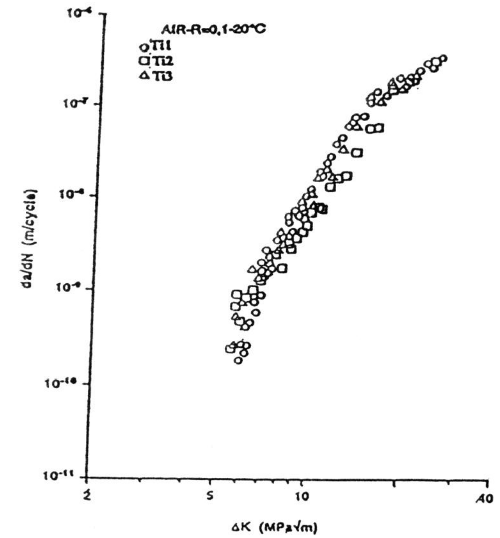


Figure 2 : Influence of microstructure on fatigue crack propagation in air at 20°C, R=0.1

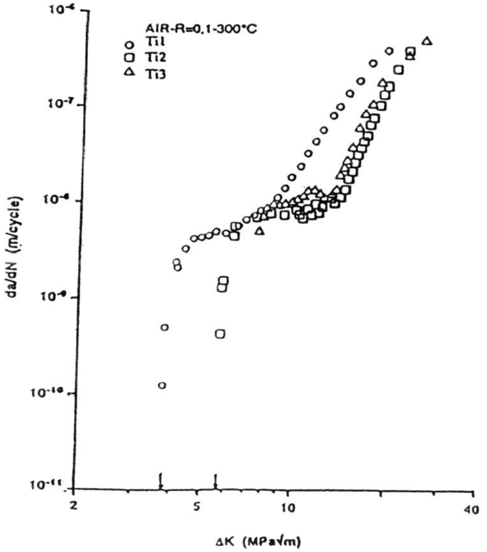


Figure 3 : Influence of microstructure on fatigue crack propagation in air at 300°C, R=0.1

To analyse these behaviors and to discriminate the influencing parameters the following procedure has been considered :

- elimination of crack closure by performing constant K_{max} tests, i.e. in condition where K_{min} is higher than the stress intensity level for crack closure : in such condition $\Delta K = \Delta K_{eff}$;
- reference tests performed in vacuum so as to determine the effective behavior of the material ;
- test performed in nitrogen atmosphere containing oxygen and water vapour with controlled partial pressure of water vapour.

Intrinsic fatigue crack propagation

Data obtained in vacuum at 300 °C from constant K_{max} tests without closure are plotted in figure 4. Two different crack growth regimes can be distinguished.

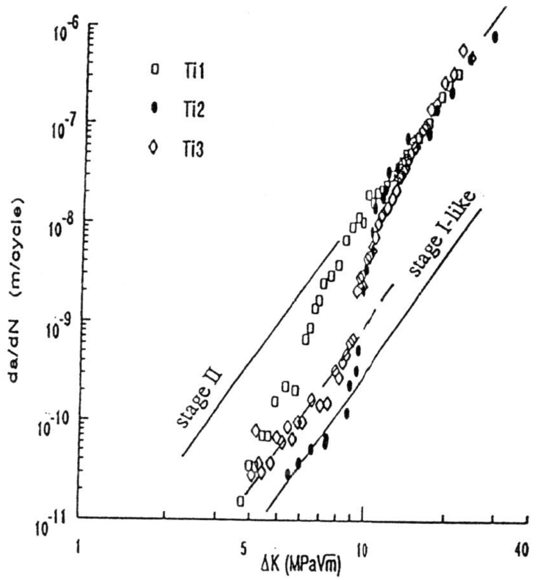
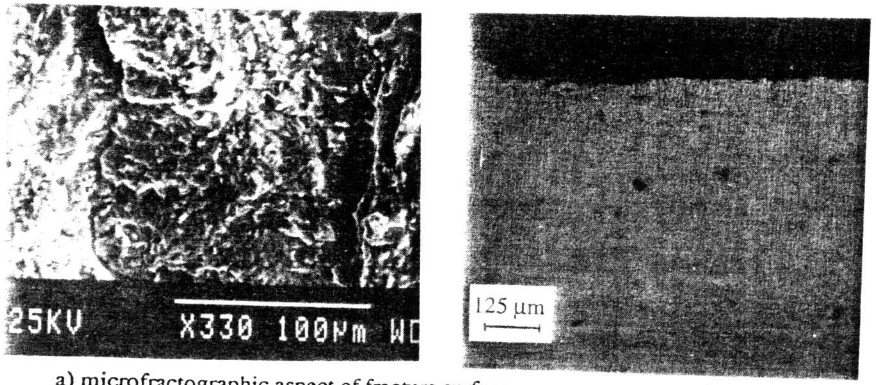


Fig. 4 - Influence of microstructure on fatigue crack propagation in vacuum at variable R, 300°C.

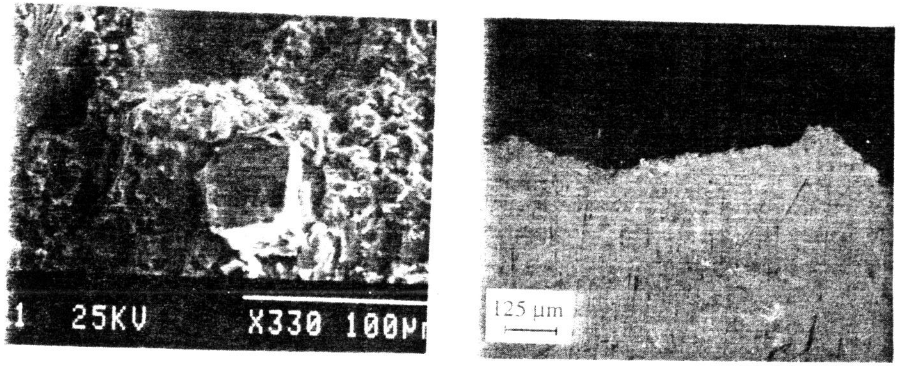
For growth rates higher than 10^{-8} m/cycle, the data are independent of the microstructure, while near-threshold $\left(\frac{da}{dN} < 10^{-8} \text{ m/cycle}\right)$ the propagation behavior is sensible to microstructure. Such behavior has been previously described in detail on Ti2 (4). The same analysis can be made for the three nuances. Microfractographic observations and crack profiles support the development of a stade II regime at mid-rates $\left(\frac{da}{dN} < 10^{-8} \text{ m/cycle}\right)$ with a flat transgranular crack path normal to the load axis (fig. 5).



a) microfractographic aspect of fracture surface

b) crack profile

Figure 5: Ti2 stage II propagation at 300°C in vacuum (da/dN = 2.10^{-10} m/cycle)



a) microfractographic aspect

b) crack profile

Figure 6: Stage I-like propagation (da/dN = 2.10^{-11}m/cycle)

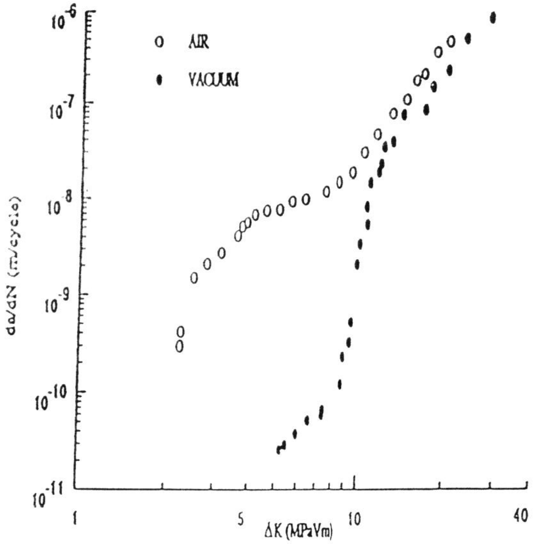


Figure 7 : Influence of environment on fatigue crack propagation for Ti2 at 300°C, variable R

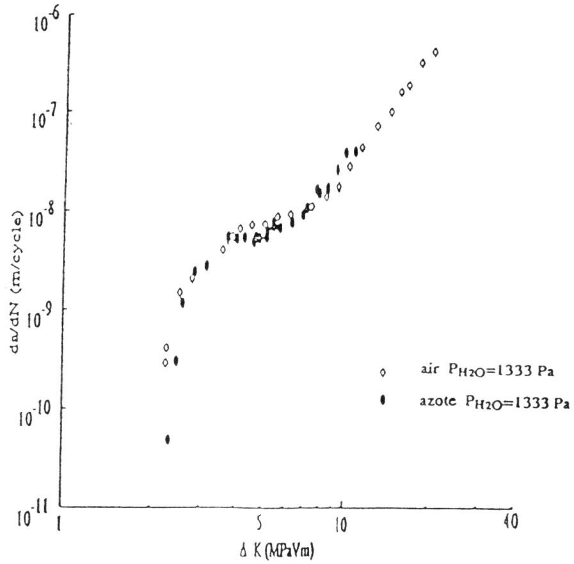


Figure 8 : Influence of water vapor at 300°C, variable R

Near threshold the existence of a crystallographic stage I-like propagation (Fig. 6) with a very rough crack path has been shown. Such propagation mechanism corresponds to a retarded propagation due to stress intensity factor shedding induced by crack deviation and branching and/or barrier effect of grain boundaries when the deformation is localized within a single slip system into each individual grain, as observed near threshold on the three nuances. These facets have been identified as basal planes from EBSP observations (5). In Ti1, which contains only 35 % of primary α, this phenomenon is not so well marked even if, in the three cases, the very near threshold behavior appears to be similar. Comparing Ti2 and Ti3 which contain both 80 % of α_p, the large size of α platelets in Ti2 lead to a higher retardation.

The influence of the temperature is illustrated in fig. 10. The stage II regime $\left(\frac{da}{dN} < 10^{-8}\ \text{m/cycle}\right)$ is rationnalized in terms of $\Delta K_{eff}/E$. The intrinsic stage II crack growth law proposed for Al alloys and steels (4) can be used and the present results confirm the existence of a single law for metallic alloy :

$$\frac{da}{dN} = \frac{A}{D_o^*} \left(\frac{\Delta K_{eff}}{E}\right)^4$$

where A is dimensionless, D_o^* is a critical cumulative displacement as defined by Weertman (6) or Rice (7), and E the Young modulus.

Influence of environment

The figure 7 shows the very large difference observed between air and vacuum at 300 °C on Ti2. The behaviors of Ti1 and Ti3 are qualitatively similar. So as to identify the active species, an experiment was performed on Ti2 in humidified nitrogen. Results are presented in fig.8. A behavior similar to the one in air is observed. The partial pressure of oxygen is 10^4 times lower than in air while the partial pressure of water vapour is similar. This result supports a predominant influence of water vapour. On going experiments will give more precise information on the kinetics of water vapour embrittlement.

It is of interest to notice the similarity with the embrittling mechanism observed at room temperature on steel as illustrated in figure 9. So the same mechanism could be suggested :

- above a critical rate (about 10^{-8} m/cycle in air) the crack propagation is only slightly accelerated due to a decrease in the surface energy induced by water vapour adsorption and which is assumed to induce a decrease in the critical cumulated displacement in relation (1) ;

- below this critical rate (which seems to correspond to a ΔK range at which the plastic zone size corresponds to the grain size, i.e. when the plastic deformation is localized within each individual grains along the crack front) a strong acceleration of the crack growth is associated to the development of an environmentally assisted mechanism which could involved hydrogen embrittlement, hydrogen being provided by the dissociation of adsorbed water vapour molecules and dragged within the slip planes by dislocations during cycling.

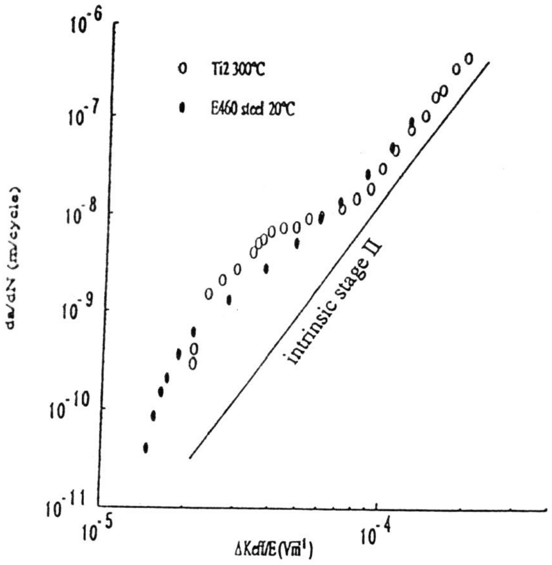


Figure 9 : Influence of environment on fatigue crack propagation for Ti2 and steel E460

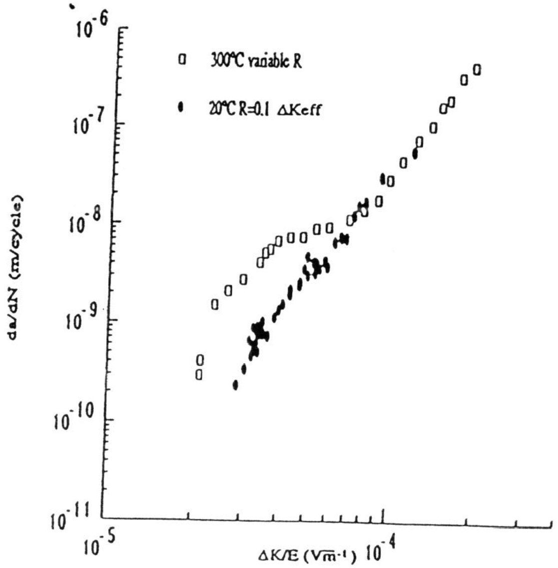


Figure 10 : Influence of temperature for effective data at 20°C and 300°C in air for Ti2

Fig. 10 compares the behavior of Ti2 in air at room temperature and 300°C ; the stage II propagation above 10^{-8} m/cycle, assumed to be assisted by water vapour adsorption, can be rationalized using $\Delta K_{eff}/E$ and thus can be described using the following relation :

$$\frac{da}{dN} = \frac{A}{D^*}\left(\frac{\Delta K_{eff}}{E}\right)^4$$

where D^* ($< D_o^*$) takes into account the influence of adsorption.

Near threshold, the additional acceleration observed at 300°C assumed to correspond to hydrogen assisted propagation, does not exist at room temperature.

On going experiment will precise the influence of microstructure on these mechanisms.

CONCLUSIONS

From fatigue crack propagation experiments conducted in vacuum, air and humidified nitrogen at 300°C on a Ti-6Al-4V alloy, the following conclusions can be drawn :

- temperature and environment have little influence on stage II propagation at rates higher than 10^{-8}m/cycle for tests performed at 35 Hz ;

- a substantial influence of a microstructure is observed at 300°C as well in air as in vacuum for growth rates lower than 10^{-8} m/cycle. The higher α_p volume fraction and the larger grain size the better resistance against propagation.

- near threshold crack propagation, a retarded crystallographic stage I-like propagation develops, resulting from the localization of the plastic strain within a single system of slip planes identified as basal planes on the basis of EBSP observations.

- water vapour has been identified as the active specie which enhanced the crack growth in ambient air and in humidified nitrogen at 300 °C.

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