INFLUENCE OF MICROSTRUCTURE ON THE FATIGUE CRACK GROWTH BEHAVIOUR OF TITANIUM ALLOYS AT HIGH TEMPERATURE

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ABSTRACT

This paper deals with fatigue crack propagation of two titanium alloys, one is an alpha-beta Ti6246, the other is a near-alpha Ti6242, forming both a Widmanstätten microstructure. Tests were carried out at three temperatures: room temperature, 425°C and 500°C in ambient air and high vacuum. It is found a better crack propagation resistance on Ti6242 alloy which presents coarse α grains associated with a great α volume fraction. The results are discussed in terms of the influence of crack closure and environmental effects on fatigue crack growth behaviour and are supported by microfractographic observations.

KEYWORDS

Titanium alloys; microstructure; fatigue, temperature.

INTRODUCTION

The investigation of the fatigue crack propagation behaviour of Titanium alloys used in turbine engines has concentrated attention of researchers in view of increase operating temperatures. Recent studies conducted in the range 300°C to 500°C have underlined the detrimental influence of ambient air (Lesterlin, 1995; Sarrazin, 1996) which can be more or less accentuated with respect to the microstructure and the composition of the alloys (Sarrazin, 1996). This paper deals with a comparative study of the behaviour of two alloys, i.e. Ti6246 and Ti6242 at 425°C and 500°C to estimate their potentiality at 500°C.

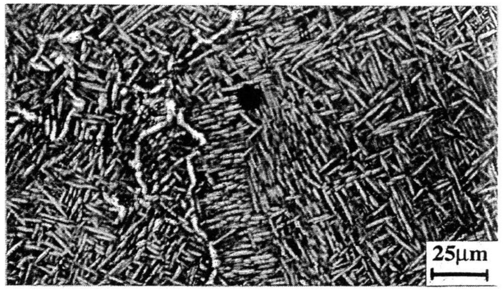
MATERIALS PRESENTATION AND EXPERIMENTAL PROCEDURE

The two titanium alloys tested are a Ti6246 type (6Al-2Sn-4Zr-6Mo)and a Ti6242 type(6Al-2Sn-4Zr-2Mo). Informations related to alloy composition, heat treatment conditions and mechanical properties are developed in table 1 and illustration of the alloy microstructures are presented in figure 1.

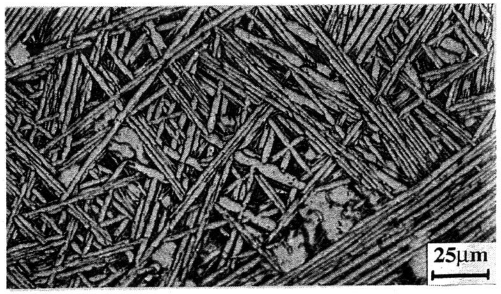
Fatigue crack growth experiments were carried out on compact tension specimens (10 mm thick and 40 mm wide) tested using a servo-hydraulic machine. Tests were performed in ambient air and high vacuum (10^{-4} Pa) from RT to 500°C. The CT specimens were 10 mm thick and 40 mm wide, the test frequency was 35 Hz and the load ratio R of 0.1 or variable for tests carried out at constant maximum stress intensity factor Kmax. Crack lengths were monitored by a potential drop method and the examinations of fatigue fracture surface morphology were made by Scanning Electron Microscopy (SEM).

Table 1. Mechanical characteristics and forging conditions

	Ti6246	Ti6242
Microstructure	Widmanstätten (intermeshing colonies)	Widmanstätten (intermeshing colonies)
forging	950°C	1030°C 1 h 00
Heating+ water quenching	930°C 2 h 00	-
Ageing + cooling	900°C 1 h 00 air cooling	970°C 1 h 00 oil cooling
Ageing	595°C 8 h 00	595°C 1 h 00
% α primary	75 %	80-90 %
α lath size (μm)	1 -50	20-70
β grain size (μm)	300	500
E (GPa)	122 (RT) 112 (300°C) 106 (425°C) 102 (500°C)	- - - -
A %	10.2 (RT) 10.9 (300°C) 14.6 (425	11.5 (RT) 12.5 (300°C) 14 (500°C)
Z %	42 (RT) - -	24 (RT) 34 (300°C°) 45 (500°C)
σ_e (MPa)	985 (RT) 753 (300°C) 725 (425°C)	1040 (RT) 800 (300°C) 725 (500°C)
σ_r (MPa)	1098 (RT) 901 (300°C) 859 (425°C)	- - -



Ti6246



Ti6242

Fig. 1. Illustration of the microstructures

RESULTS and DISCUSSION

The fatigue crack propagation of the two alloys was first investigated at Room Temperature (RT). The crack growth rates are plotted in figure 2 as a function of the stress intensity factor range in conventional log-log diagrams. In figure 3 are presented the same data after correction for crack closure and the figure 4 shows the evolution of the stress intensity level for crack opening Kop. For growth rates higher than 10-7 m/cycle, the two nominal curves (da/dN vs ΔK at R=0.1) and the effective curves (da/dN vs ΔKeff) are very similar. At lower rates the general trend is a better resistance of the Ti6242 alloy with a substantially higher theshold. The correction of crack closure does not eliminated this discrepancy but enhances the difference specially in the threshold range. Comparison with the reference propagation curve obtained in high vacuum puts in light the role of environment which appears very much more marked for the Ti6246 alloy. Such an effect is generally attributed to a detrimental influence of water vapour (Lesterlin, 1996; Hénaff, 1996). But the higher sensivity of Ti6246 to water vapour at RT is still unexplained.

The morphology of the fracture surfaces in figures 13a and 13b, indicates a trend to a crystallographic propagation in the near-threshold region for both alloys with the presence of large facets corresponding to the average size of grains, and then being substantially larger in the coarser Ti6242 microstructure. However, the figure 4 which illustrates Kop as a function of ΔK, shows that there is no real correlation between the apparent roughness and the closure contribution which is more important on the Ti6246 in the lower ΔK range.

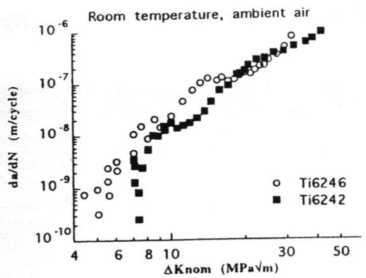


Fig.2 : Nominal propagation at RT in ambient air

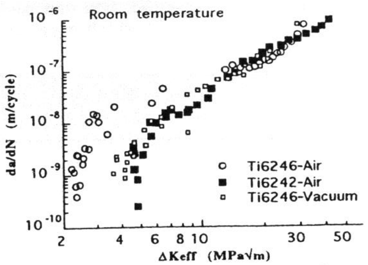


Fig.3 : Effective propagation at RT

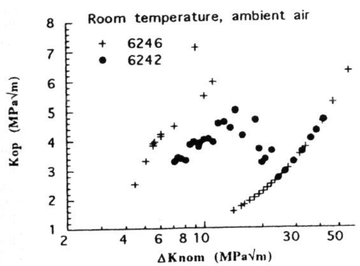


Fig.4 : Evolution of Kop vs ΔK at RT in air

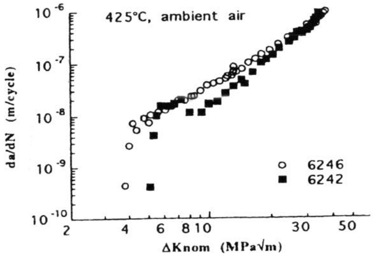


Fig.5 : Nominal propagation at 425°C

The nominal and effective propagation curves at 425°C are respectively plotted in figures 5 and 6 and the corresponding Kop evolution is presented in figure 7. The crack propagation resistance of Ti6242 is, as at RT, slightly better than that of the Ti6246 alloy, the difference being more noticeable in the threshold area. But after closure correction, the effective behaviour of the two alloys becomes very similar. The fracture surface morphology (figures 13c and 13d) is consistent with a flatter crack path than at RT with a smoother influence of microstructure. It is also in accordance with a lower contribution of the roughness induced closure (Suresh and Ritchie, 1983) than at RT.

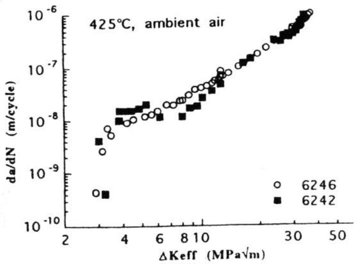


Fig.6 : Effective propagation at 425°C in ambient air

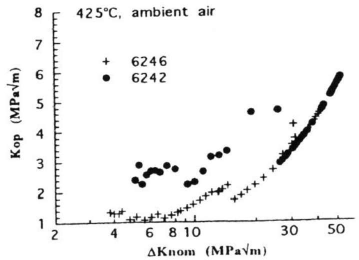


Fig.7 : Evolution of Kop vs ΔK at 425°C

The difference in the nominal data can be here explained by the very small closure effect observed on Ti6246 (figure 7) which presents a flatter crack path than the Ti6242 specimen.

At 500°C (figures 8 and 9), the nominal and effective propagation behaviours of the two alloys are very similar for growth rate higher than the typical plateau range observed at $2x10^{-8}$ m/cycle. But near the threshold, the Ti6242 presents here again a better resistance than the Ti6246 with a higher nominal threshold range (figure 8). After correction for crack closure, the difference between the two alloys becomes much accentuated due to a very low effective threshold range for the Ti6246 alloy. For comparison purposed, effective data in high vacuum are plotted in figure 9. The poor resistance of Ti6246 is clearly related to a very much higher sensivity of this alloy to air environment. As reported elsewhere (Lesterlin, 1996; Hénaff,1996), this environmental effect has been clearly attributed to air moisture.

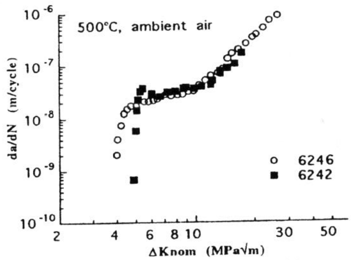


Fig.8 : Nominal propagation at 500°C in air

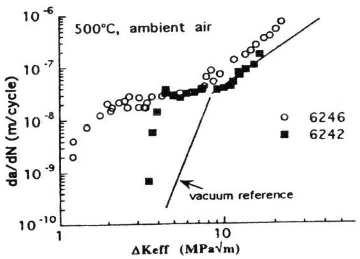


FIg.9 : Effective propagation at 500°C in air and high vacuum

The closure contribution is very much more important on the Ti6246 alloy than on the Ti6242 (see Fig.10). As at RT the morphology of the fracture surfaces of the Ti6242 exhibit a higher roughness which is not in accordance with the smaller closure contribution. The oxide thickness, which can be estimated on the basis of the oxide coloration, i.e. 60 nm to 80 nm on Ti6246 (yellow to purple) and about 100 nm on Ti6242 (blue), could explain the closure contribution, the effective ΔCTOD at threshold being very much lower on Ti6246 when considering the effective stress intensity factor range. It could be suggested a predominant roughness induced closure for the Ti6242 type and a predominant oxide wedging effect (Suresh, 1981; liaw, 1982) for the Ti6246 type. This analysis can be reinforced by the results presented in figure 11.

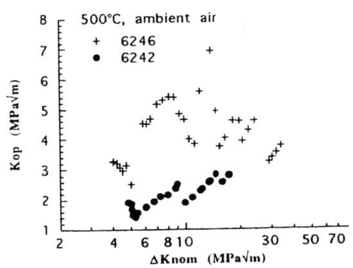


Fig.10 : Evolution of Kop vs ΔK at 500°C

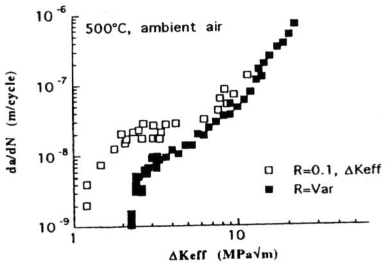


Fig.11 : Influence of R ratio at 500°C on Ti6246

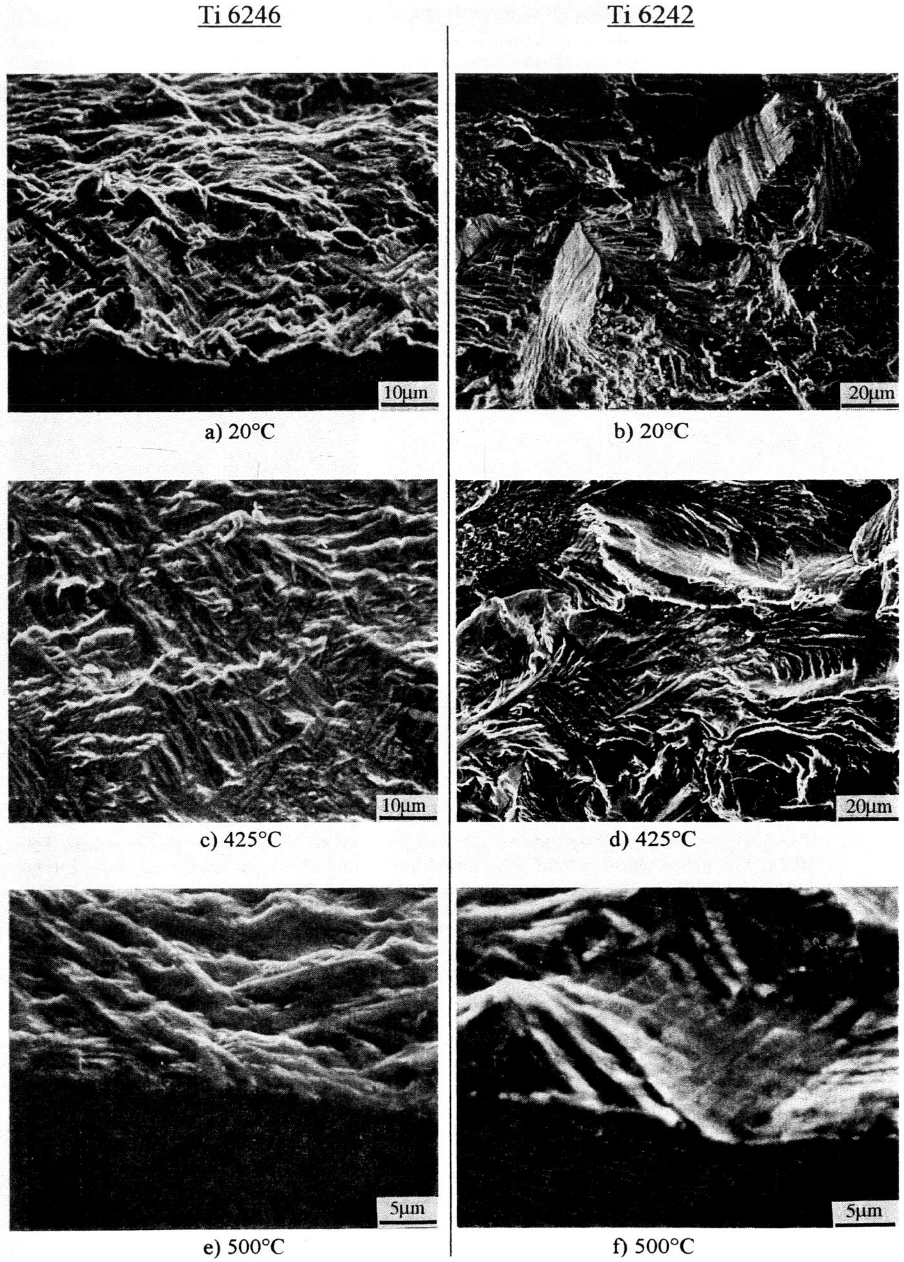
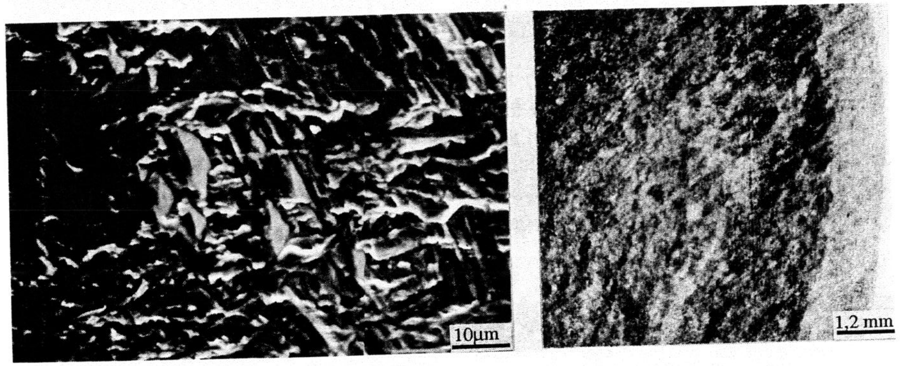
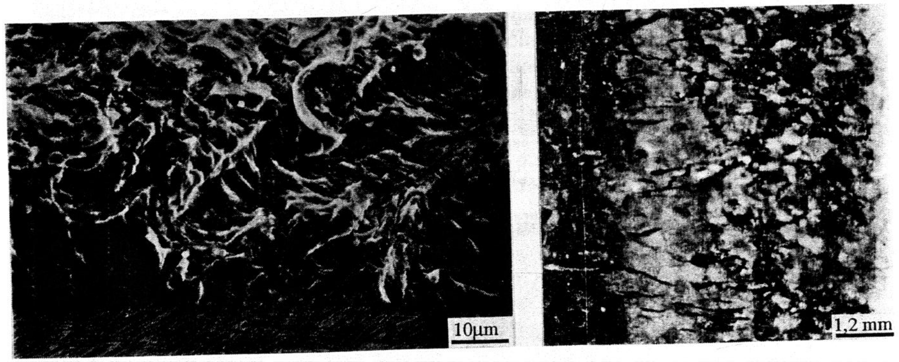


Figure 13 : Cracked surfaces obtained on Ti 6246 and Ti 6242 at R=0,1 at room temperature (a & b), 425°C (c & d) and 500°C (e & f) in the near threshold range.

Ti 6246



a) R=0,1



b) R=VAR

Figure 14 : Cracked surfaces obtained on Ti 6246 at 500°C from tests performed at R=0,1 (a) and R=VAR (b) at 10^{-8} m/cycle.

A constant Kmax test was performed on the Ti6246 alloy, in conditions where closure did not occur, the R ratio being sufficiently high to have Kmin>Kop at any stage of the propagation. Surprisingly, the propagation curve obtained in these conditions corresponds to slower crack growth rates and to a higher threshold range than the effective propagation obtained after closure correction while in high vacuum there was no difference. This result indicates a higher influence of water vapour when operating at a low R ratio (R=0.1). This suggests that closure induces a rupture of the oxide film at low R ratio while the oxidized surfaces would inhibit the detrimental effect of water vapour when operating at high R ratio to avoid closure.
The observations of the fracture surfaces (figure 14) indicate a much flatter crack path at R=0.1 (fig.14a) suggesting that asperities such as that observed at high R ratio (fig.14b) are reduced by the compression of the two surfaces when they are in contact during the closure sequence of the loading cycle.
These experiments underline the complexity of the interactions existing between microstructure, closure and environment, specially at high temperature. On going experiments will give a better understanding of these phenemena with a special attention to the role of the test frequency (i.e. the time) which has been shown to have a great influence. Indeed, a first series of experiments was carried out on the Ti6246 alloy at various test frequencies (Lesterlin, 1996). Propagation data at 0.1 Hz in air are plotted in figure 12 and this regime has been shown to correspond to a corrosion fatigue mechanism induced by atmospheric water vapour which can be described using a relation based on the crack tip opening displacement ΔCTOD related to the increment per cycle as follows (Pelloux, 1970) :

$$da/dN = 0.5\ \Delta CTOD.$$

Some crack growth rate measurements performed at 0.1 Hz on the Ti6242 alloy and experimental data obtained in air at 593°C on a Ti1100 alloy (Ghonem, 1991; Foerch, 1992) are also plotted in the same figure. The crack growth acceleration observed at 0.1 Hz is much more important on the Ti6246 than on the TI6242 type even still on Ti1100 alloy. Indeed, the Ti1100 propagation curve, obtained from test performed at low frequency (0.05 Hz) and at 593°C (i.e. 100°C higher than for the other alloys) is very similar to that of Ti6246 alloy at 35 Hz tested at 500°C. These results confirm the much lower sensivities of Ti6242 and Ti1100 to water vapour at 500°C and suggests that the critical temperature step existing between 425°C and 500°C for the Ti6246 could be shift at a higher temperature for the Ti6242 and even more for the Ti1100 alloy.

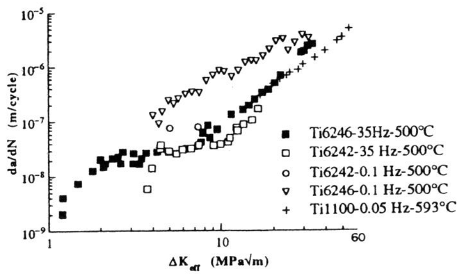


Fig.12 : Comparison of fatigue crack growth data at 500°C in Ti6246 and Ti6242 and at 593°C in Ti1100 (Ghonem, 1991; Foerch,1992)

CONCLUSION

This study of the fatigue crack propagation in two titanium alloys Ti6246 and Ti6242 dedicated to high temperature applications leads to the following conclusions :

- high temperatures (425°C to 500°C) have little influence on the intrinsic propagation as observed in high vacuum, but induce an important decrease in the resistance against propagation in ambient air.
- the interactive influence of air environment and temperature, previously attributed to a detrimental effect of water vapour, is much more accentuated on the Ti6246, specially above 425°C.
- the role of roughness induced closure is discussed with respect to microstructure.

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