Damage tolerance issues peculiar to supersonic civil transport aircraft

Grégory Odemer, Gilbert Hénaff, Bertrand Journet, Luc Rémy, Nader Haddar, Alain Köster

DAMAGE TOLERANCE ISSUES PECULIAR TO SUPERSONIC CIVIL TRANSPORT AIRCRAFT

G. ODEMER[1], G. HENAFF[1], B. JOURNET[2], L. REMY[3], N. HADDAR[3], A. KOSTER[3]
[1]Laboratoire de Mécanique et de Physique des Matériaux, UMR CNRS n°6617, ENSMA, 86961 Futuroscope Chasseneuil, France
[2]Département Ingénierie des Structures, EADS CCR, 92152 Suresnes, France
[3]Centre des Matériaux, Ecole Nationale Supérieure des Mines de Paris/ARMINES, UMR CNRS n° 7633, 91003 Evry, France

ABSTRACT

This paper presents results of experimental investigations on creep, fatigue and creep-fatigue crack growth behaviour of the 2650-T6 aluminium alloy in temperature, along with numerical simulation of stress distribution around the tip. The results will provide a preliminary database on the fatigue properties of the 2650 T6 alloy under loading representative of service conditions and predict the damage tolerance assessment of the future civil transport aircraft fuselage.

Testing were carried out to evaluate the effect of creep-fatigue interaction and get insight into the damage processes. Numerical simulation of stress field around the crack tip were performed to account for the observed behaviour. The crack growth rates measured on CT specimens were correlated with the stress intensity factor K. In creep tests, an influence of the initial value of K on the low crack growth rates is shown. The behaviour is not deeply affected by temperature in the range 100-130°C. However, at 160°C, crack growth rates are faster than at 130°C due to an increase of creep contribution in local stress-strain response, that might be enhanced by ageing. In fatigue (triangular wave loading), no difference is noticed in crack growth rates at 20 and 130°C. In creep-fatigue, the crack growth rates (trapezoidal wave loading) at 130°C are faster than during creep or fatigue crack growth in a given domain of K. The fracture surfaces indicate that creep-fatigue interaction is characterised by a higher portion of intergranular fracture. Thus, a detrimental creep-fatigue interaction at 130°C has to be taken into account in crack propagation law used in damage tolerance analysis.

The constitutive law used in the calculations for numerical simulation was identified on the basis of cyclic relaxation tests. The computation results indicate that the von Mises stress at the beginning of dwell during creep-fatigue is higher than in the case of creep and fatigue.

1 INTRODUCTION

Concorde was originally designed to sustain a total of 15000 hours under a maximum temperature of 130°C at a cruise speed of Mach 2.05. At that time, the damage tolerance philosophy was not mature yet. The future supersonic aircraft will be designed to sustain a total of 60000 h under the same temperature and will have to meet damage tolerance requirements. Therefore, issues related to creep-fatigue interaction and ageing can be expected and have to be taken into account in the damage tolerance assessment of the aircraft. Indeed, few researchs have examinated light alloys under creep conditions [1][2] and none under creep-fatigue conditions.

A collaboration between two academic laboratories, LMPM (ENSMA) & CdM (ENSMP/ARMINES), and the Corporate Research Center EADS, was established within the framework of a national program in order to investigate the damage tolerance of the new aluminium alloy succeeding as 2218A. LMPM has to examinate the 2250 T6 creep-fatigue crack growth behaviour and CdM has to propose a numerical simulation of the stress distribution around the tip for the observed behaviour.

Three types of mechanical tests were employed to characterize the crack growth resistance of this alloy : creep (constant load), fatigue (triangular loading) and creep-fatigue (trapezoidal loading with 300s at maximum load) at the reference temperature of 130°C and, for comparison purposes, at 20°C, 100°C and 160°C. The crack growth rates measured on CT specimens were correlated with the stress intensity factor K. The observations of fracture surfaces help to understand the damage processes.

In this research, a numerical simulation of the stress distribution is developed by CdM according to experimental results under the three types of tests at 130°C. The aim is to describe the plastic zone size at the tip of the crack for a CT specimen in creep-fatigue conditions.

2 EXPERIMENTAL CONDITIONS

The 2250 T6 alloy is an aluminium copper-magnesium alloy. The precipitation hardening has been studied by G.Lapasset and al [3]. The alloy is heat-treated at 192°C for 21 h. The chemical composition is presented in Table 1.

CT type specimens 40 mm in width were used and machined in the L-T orientation. The specimens were fatigue precracked (1 mm long precrack) using a servo-hydraulic system. The potential method is used to measure the crack length [4]. The crack length is related to the potential by empirical eqn (1) and the stress intensity factor K is calculated by means of eqn (2):

$$a/W = -5{,}5607 + 17{,}808\,(V/Vo) - 23{,}603\,(V/Vo)^2 + 16{,}629\,(V/Vo)^3 - 5{,}8964\,(V/Vo)^4 + 0{,}82949\,(V/Vo)^5 \quad \text{eqn (1)}$$

$$K = [\,(P / (b.W^{0,5})\,)*(2+ a/W)*(\,f(a/W)\,)\,] / [(1-a/W)^{1,5})] \qquad \text{eqn (2)}$$

$$\text{avec } f(a/W) = 0{,}886 + 4{,}64\,(a/W) - 13{,}32\,(a/W)^2 + 14{,}72\,(a/W)^3 - 5{,}6\,(a/W)^4$$

Table 1: Composition of constituent elements in aluminium 2650 T6.

Analyse	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Zr
Min	0.36	0.08	2.60	0.32	1.50				0.08	
Visé	0.40	0.11	2.70	0.35	1.60				0.10	
Max	0.44	0.13	2.80	0.38	1.70	0.04	0.03	0.10	0.12	0.03

2.1 Creep and fatigue crack growth results

The creep curves da/dt vs K indicated a marked influence of the initial value of K, K_0, as shown in figure 1. The higher its value, the faster the initial creep crack growth rate. Moreover, the behaviour is not affected by temperature in the range 100-130°C. However, at 160°C, crack growth rates are faster than at 130°C, due to an increase of creep contribution in local stress-strain response, that might be enhanced by ageing. Indeed, in this case, the temperature is close to the heat-treatment temperature and specimens are tested during 20 days. The rupture surfaces shown in figure 2, exhibit a predominant intergranular fracture mode in the steady-state crack growth (Paris domain). In fatigue, it is observed in figure 3, that the propagation is not affected by temperature or frequency and only slightly by the loading ratio R. The fracture mode is mainly transgranular in the steady-state regime, as shown in figure 4.

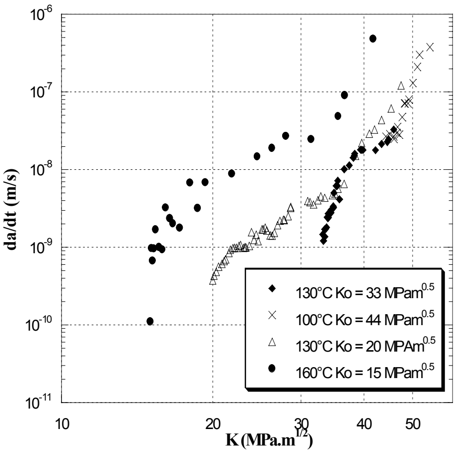

Figure 1: Creep crack growth rate for different temperatures and initial loads.

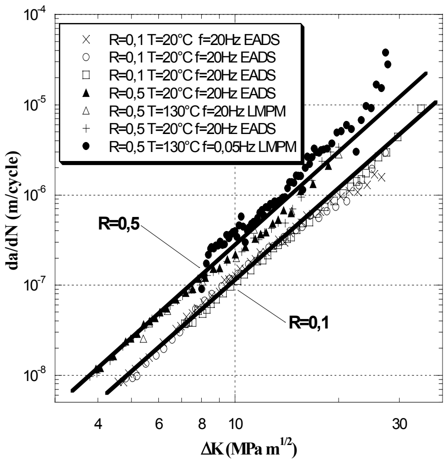

Figure 3: Fatigue crack growth rate for different load ratios, temperatures and frequencies.

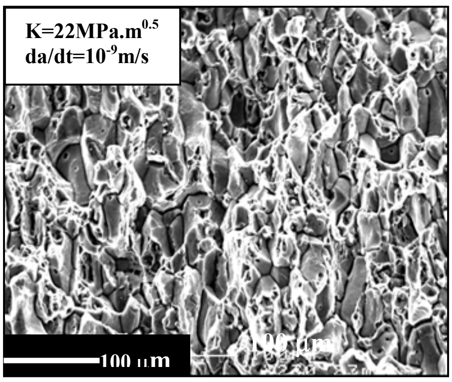

Figure 2: Creep rupture surface (predominant intergranular fracture mode).

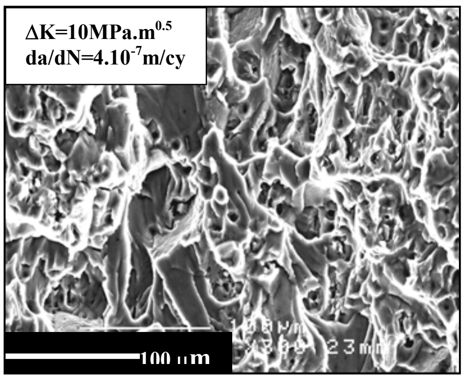

Figure 4: Fatigue rupture surface (predominant transgranular fracture mode).

2.2 Creep-fatigue tests

The results indicate a deleterious influence of the dwell time on the crack growth for $\Delta K < 20 MPa.m^{0.5}$ as shown in figure 5. For $\Delta K > 20$ $MPa.m^{0.5}$, this influence progressively decreases. Additionnally, it is not possible to describe this influence by a simple cumulative rule of the crack advance due to creep and the crack advance due to fatigue. This is indicative of a creep-fatigue interaction. The fractographic observations, presented in figure 6, reveal that the dwell time introduces intergranular decohesions in a predominant ductile propagation.

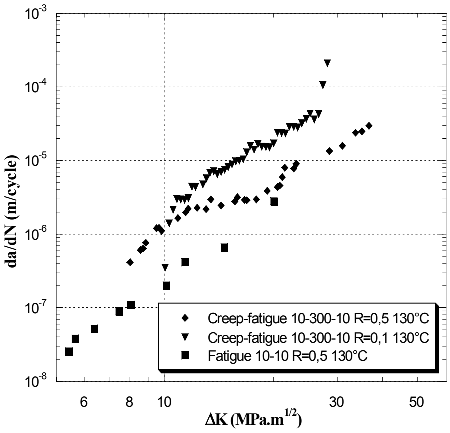

Figure 5: Creep-fatigue and fatigue crack growth rate for different ratios.

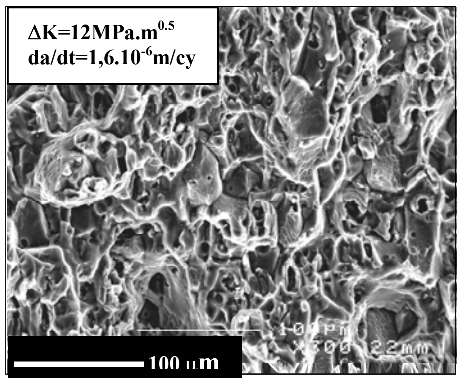

Figure 6: Creep-fatigue ductile propagation with Intergranular decohesions.

3 NUMERICAL SIMULATION OF CYCLIC BEHAVIOUR

A unified viscoplastic model (Chaboche 1977) was used to describe alloy behaviour. The viscoplastic cumulative $\dot{p}$ was written as a power law (eqn 3):

$$\dot{p} = \left\langle \frac{J_2(\sigma - X) - R}{K} \right\rangle^N \qquad \text{eqn (3)}$$

where K et n are two parameters, J_2 is von Mises invariant, σ is the stress tensor, X and R are kinematic and isotropic hardening variables. Isotropic hardening is considered constant and kinematic hardening is non linear with $X = \frac{2}{3}C\alpha$ and $\dot{\alpha} = \dot{\varepsilon}_p - D\alpha.\dot{p}$. This model is known to yield a fairly good desciption of Bauschinger's effect. This model was identified on cyclic relaxation tests at 130°C and was shown to describe fairly well the rapid transient behaviour as well as the stress relaxation during strain holds at different maximum strains.

The aim of the simulation is to describe the stress distribution of the crack tip as a function of time. A 2D finite element analysis of a stationary crack was carried out assuming either plane stress or plane strain conditions for creep, fatigue and creep-fatigue for a loading ratio R=0,5. The extent of the plastic zone was shown to vary according the loading wave shape. For brevity, only the von Mises is plotted as a function of the distance ahaead of the crack tip for a plane stress assumption in figures 7, 8 and 9. Under creep the von Mises stress decreases with distance ahead of the crack for a given time and the whole curve decreased with increasing time. Under fatigue loading maximum von Mises varies as under creep at the first cycle while the minimum stress decreases rapidly as a function of distance aahead of the crack and these show little varaation with the number of cycles. Creep-fatigue show a more complex variation of stress as function of distance. In particular the von Mises stress is higher at the beginning of the hold time than under fatigue loading. This can provide an explanation of the higher growth rate under creep-fatigue than under fatigue. This phenomenon can be triggered by the occurrence of creep damage during the hold time since the stress remains reamins fairly high.

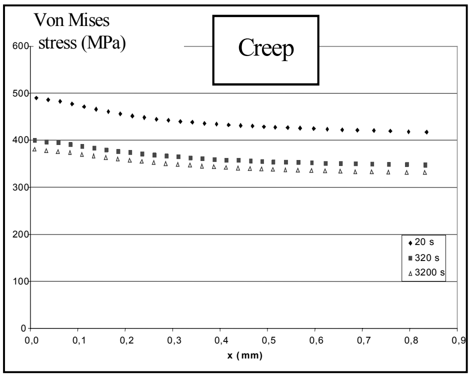

Figure 7: Evolution of Von Mises stress versus the distance to the crack tip for creep loading.

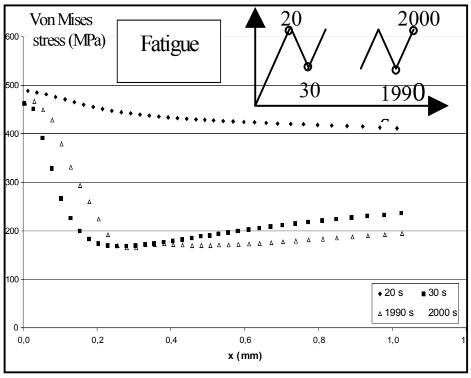

Figure 8: Evolution of Von Mises stress versus the distance to the crack tip for fatigue loading.

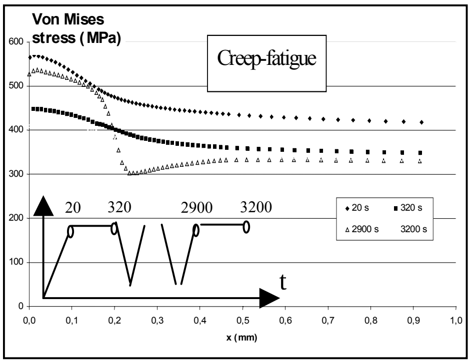

Figure 9: Evolution of Von Mises stress versus the distance to the crack tip for creep-fatigue loading.

CONCLUSION

The preliminary results have demonstrated the occurrence of creep-fatigue interactions during crack growth in the 2650 alloy under load signals representative of in-service conditions. This effect has to be taken into account in the damage tolerance assessment of the fuselage. On going work will aim to characterise the influence of various parameters such as dwell time and load ratio on these interactions. Numerical computation will be used to assess long-term predictions on the basis of accelerated laboratory testing.

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