AN ANALYSIS OF THE ENVIRONMENTAL INFLUENCE ON THE NEAR-THRESHOLD FATIGUE CRACK PROPAGATION BEHAVIOUR OF STEELS

G. HÉNAFF and J. PETIT *

On the basis of experimental data, an analysis of environmental influence on the near-threshold behaviour of steels is developped by considering two distinct processes: the adsorption of water-vapour molecules on freshly created surfaces and a subsequent hydrogen-assisted cracking mode. A crack growth law is proposed to describe the observed behaviour .

INTRODUCTION

Engineering structures are used in more and more severe conditions. In particular, as the number of loading cycles increases, the determination of the fatigue crack growth behaviour of the materials used has to be extended to the slow crack growth rate regime. Such a determination must take into account two salient features of the propagation in this regime: crack closure effects, which might reduce the effective value of the stress intensity factor range at the crack tip, and environmental influence which induces higher crack growth rates than those obtained in an inert environment. So, the evaluation of the environmental contribution to the crack growth process implies the previous determination of the crack propagation in an inert environment. Besides, the analysis of this environmental influence cannot be correctly conducted without considering the effective value of the stress intensity factor range at the crack tip, i.e. without correcting the possible crack closure effects.

* Laboratoire de Mécanique et de Physique des Matériaux, URA CNRS 863
ENSMA, 20 rue Guillaume VII - 86034 POITIERS CEDEX FRANCE

According to the literature now well documented on this topic, the crack growth enhancement which can be observed in gaseous environments such as ambient air, purified inert gases containing traces of water vapour and low pressures, results from a strong interaction between the mechanical cyclic loading and the exposure of the crack tip to water vapour molecules [1, 2, 3]. However the physical processes involved in this phenomenon are far from being well-known.

In this paper, the near-threshold behaviour of a high-strength low-alloy steel has been investigated under different environmental conditions in order to elucidate some of these processes. The ability of existing fatigue crack growth theories to suitably describe the action of these processes is also discussed.

EXPERIMENTAL CONDITIONS

The material considered here is a high-strength low-alloy steel 30NCD16 in a quenched tempered state, having a Young's modulus 191GPa, 0.2 % proof stress 1130 MPa, tensile strength 1270 MPa, elongation 13 %. The specimens were compact-tension with dimensions width W=75mm and thickness B=12mm . The crack length was optically measured by mean of a travelling microscope.

Fatigue tests were conducted on a servo-hydraulic machine equiped with a chamber specially designed to provide high ($p=10^{-3}$Pa) or primary (p=1Pa) vacuum conditions. Residual gases analysis for the two environments is presented in figure 1. It comes out that the atmosphere mainly consists, in both cases, of water vapour (75% in primary vacuum; 50% in high vacuum).

A high value of the load ratio (R=0.7) has been selected in order to avoid any crack closure occurence. Nevertheless a special attention has been paid during each experiment to check the lack of crack closure on the basis of measurements performed using a compliance technique. A digital oscilloscope performed load *vs* displacements recordings at test frequency.

RESULTS

vacuum

The results obtained in high vacuum at 35Hz are presented in figure 2. They exhibit a linear relationship between the crack growth rates and the effective cyclic stress intensity factor ΔK_{eff} throughout the whole explored range, with a slope m close to 4. As high vacuum was assumed to constitute an inert environment, it was logically expected that the test frequency would have no influence on crack growth rates. However, a crack growth enhancement was obsersed when lowering the test frequency down to 0.2Hz, as shown in figure 2. Two extreme regimes can be observed. The lower one corresponds with the behaviour observed at 35 Hz. The upper regime (0.2Hz) is once again depicted by a linear relationship with a slope m=4. For a given frequency in the range 0.2 to 35 Hz, the curve first follows the upper regime. Then, once a critical value of the crack growth rate is reached, a transient behaviour is observed before the curve recovers the lower regime.
Crack growth rates measured under primary vacuum conditions at 35Hz are presented in figure 3. Data correspond with the upper regime obtained in high vacuum at 0.2 Hz.

Ambient air

The results obtained in air are presented in figure 4. Different stages appear, resulting in growth rates significantly higher than in vacuum under the same loading amplitude:

- 5×10^{-8} m/cycle < da/dN < 10^{-7} m/cycle: the curve merges in the ones obtained, in the same range, in primary vacuum and at low frequency in high vacuum. One might therefore conclude that the same process governs the propagation in this regime under the three environmental conditions.

- 10^{-9} m/cycle < da/dN <5×10^{-8} m/cycle : a radical change in the slope of the curves ($m = 4 \rightarrow m = 2.7$) suggests that another process takes place. Intergranular facets can be observed on rupture surfaces in this range.

- da/dN < 10^{-9} m/cycle : the crack growth rates are highly decreased as the ΔK_{eff} value decreases, as generally noticed in the near-threshold region.

DISCUSSION

The analysis of environmental influence on fatigue crack growth has been conducted by comparing effective data obtained for different conditons of exposure to water vapour with effective data obtained in an inert environment. Only the main features are presented here.

Intrinsic behaviour

The behaviour observed in high vacuum for high frequencies can be correctly depicted by a modified Weertman law [4, 5, 6]:

$$\frac{da}{dN} = \frac{A}{D_0^*}\left(\frac{\Delta K_{eff}}{\mu}\right)^4 \qquad (1)$$

with: A = dimensionless constant ; μ = shear modulus; D^*_0 = critical value of the cumulated displacement.

Adsorption

The influence of the test frequency on crack growth ratse in high vacuum has been previously analysed [7] and has been attributed to the adsorption of water vapour molecules present in this atmosphere (cf fig 1a) onto freshly created rupture surfaces. A model has been proposed , which shows that this process is controlled by the transport of active species to the crack tip where they are adsorbed. This adsorption process induces a decrease of the D* value, depending upon the coverage rate θ of rupture surfaces by adsorbed molecules. At saturation ($\theta = 1$), which is always the case in primary vacuum, $D^* = D^*_1$.

Ambient air

The confrontation between data sets obtained in air in the upper stage and in the adsorption saturating state in vacuum suggest that, in air and in this range, the influence of environment is limited to an adsorption effect. However, for da/dN<5 x 10^{-8} m/cycle, another mechanism takes place, corresponding with the apparition of intergranular facets on rupture surfaces. These facets support the existence of a hydrogen-assisted propagation [8]. On this basis, a new formulation is proposed here, which tries and takes into account the action of two distinct processes:

- a cumulative damage process, similar as in inert environment, but enhanced by the adsorption of water vapour molecules on feshly created rupture surfaces
- a propagation process assisted by the hydrogen resulting from the dissociation of adsorbed molecules and dragged into the material plastically strained ahead of the crack tip; this process can be described by using a COD-criterion-based model [9, 10, 11].

The term relative to the propagation assisted by adsorption is similar to Eq. 1 by considering D^*_1 instead of D^*_0. The hydrogen-assisted cracking mode is derived in a semi-empirical way by considering the effective stress intensity range at the crack tip and by incorporating the effective threshold value. One thus obtains:

$$\frac{da}{dN} = \frac{A}{D_1^*}\left(\frac{\Delta K_{eff}}{\mu}\right)^4 + B\frac{\left(\Delta K_{eff}^2 - \Delta K_{eff\,th}^2\right)}{\mu\sigma_0} \qquad (2)$$

with: B: dimensionless constant - σ_0: yield strength - $\Delta K_{eff\,th}$: effective value of the threshold stress intensity factor range.

The computed results are represented by the solid line in figure 4. They show a good agreement with experimental data.

CONCLUSION

The analysis of the near-threshold behaviour of a high-strength low-alloy steel, conducted here by correcting possible crack closure effects, has emphasised the influence of water vapour on fatigue crack propagation, even in the case of very low partial pressure. This influence splits up into two distinct processes:

- the adsorption of water vapour molecules on feshly created rupture surfaces
- a hydrogen-assisted cracking mode

By surperposing two basic models, a new crack growth law has been derived to describe the action of these two processes.

ACKNOWLEDGEMENTS

This work has been carried out under the financial support of the Louis-Blériot Joint Research Center of Aérospatiale in Suresnes. The authors also wish to thank Dr B. Bouchet who performed the residual gases analyses.

REFERENCES

(1) Achter, M. R., "Fatigue Crack Propagation", ASTM STP 415, 1967, pp. 181-202.

(2) Wei, R. P., Simmons, G. W., Int. Journ. of Fract., Vol. 17, n°2, 1981, pp. 235-247

(3) Bignonnet, A., Loison, D., Namdar-Irani, N., Bouchet, B., Kwon, J. H., Petit, J. "Fatigue Crack Growth Threshold Concepts", Eds. D.L. Davidson and S.Suresh, TMS aime, Warrendale, 1984, pp. 99-113

(4) Weertman, J., Int. J. Fract. Mech., No 2, 1966, pp.460-467

(5) Petit, J. "Fatigue Crack Growth Threshold Concepts", Eds. D.L. Davidson and S. Suresh, TMS aime, Warrendale, 1984, pp. 3-25

(6) Petit , J. and Hénaff, G. , Scripta Met. et Mat., Vol 25, 1991, pp. 2683-2687

(7) G. Hénaff and J. Petit, submitted to Acta Met., 1991.

(8) C.E. Richards and T.C. Lindley , Eng. Fract. Mech., Vol. 4, 1972, pp. 951-978

(9) Davidson, D. L., Fat. Eng. Mat. & Str., Vol. 3, n° 1, 1981, pp. 229-236

(10) Mc Clintock, F. A., "Fatigue Crack Propagation", ASTM STP 415, 1967, pp.170-172

(11) Pelloux, R. M. N., Eng. Fract. Mech., Vol. 1, 1970, pp. 697-704

(12) Davidson, D. L., and Lankford, J., Fat. Eng. Mat. & Str., Vol 7, n° 1, 1984, pp. 29-39

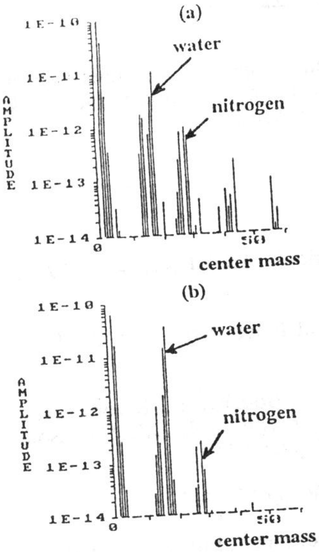

Figure 1 : residual gases analysis
(a) high vacuum (b) primary vacuum

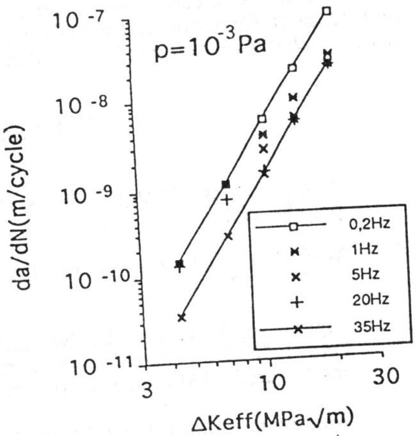

Figure 2 : fatigue crack growth data in high vacuum

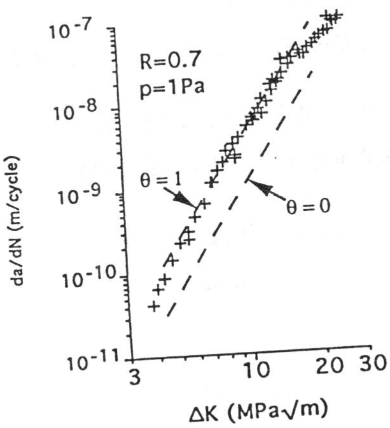

Figure 3 : fatigue crack growth data in primary vacuum

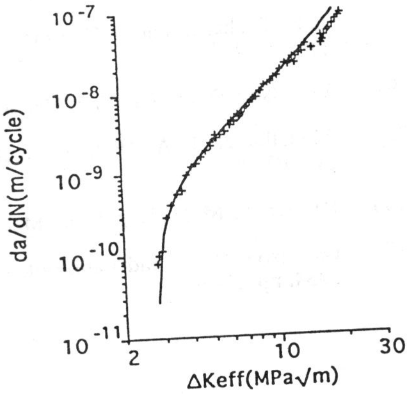

Figure 4 : fatigue crack growth data in air compared to model