CREEP-FATIGUE CRACK GROWTH MODELLING BASED ON LOCAL AND GLOBAL APPROACHES FOR 316L(N) STAINLESS STEEL

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During high temperature service, macroscopic cracks can initiate and propagate in metallic components subjected to complex loading history. Fracture mechanics concepts are widely used in defect assessment procedures. For creep ductile materials, correlations are based on the C* loading parameter, generally used for large scale secondary creep conditions. Since the 316L(N) stainless steel exhibits a large primary creep effect, the C^*_h loading parameter is more suitable, at least on the onset of a pure creep test.

In this paper, an attempt is made to mathematically analyse pure creep crack growth tests with both C^*_h and C* parameters, taking advantage of the proportionality between the crack extension Δa and the loadline displacement history. An alternative method, based on the local approach, is discussed briefly. The global approach concepts are applied on creep-fatigue crack growth tests.

INTRODUCTION

Defect assessment procedures for components operating at high temperature use fracture mechanics concepts in order to predict either crack initiation time or crack growth rate. The introduction of loading parameters such as C^*_h or C* is necessary for creep and creep-fatigue analyses. These two parameters have two different units and need a transition time definition between large scale primary creep (C^*_h) and large scale secondary creep (C*) regimes. In this paper, we first describe test results obtained on CT specimens under pure creep and creep-fatigue with long dwell loadings. These results clearly show that the crack advance and the creep loadline displacement are proportional. Therefore, an explicit mathematical function linking da/dt (noted $\dot{a}$) to C* (or C^*_h) can be found. The classical way to predict crack growth rate proposed in the defect assessment procedures can then be developed without using $\dot{a}$-C* correlation. Furthermore, the change of parameter units (C^*_h and C*) can be avoided by integrating directly piecewise functions in order to predict the crack propagation. An alternative method which avoids this difficulty is based on the local approach, which deals with a dimensionless damage parameter. The last part of the text is devoted to the application of the above global approach on creep-fatigue tests and to the discussion.

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EXPERIMENTAL EVIDENCE

Both creep and creep-fatigue tests have been carried out on 316L(N) material CT specimens at 650°C (1). The load-line displacement is recorded by means of an extensometer attached to the specimen. The crack growth is monitored by a potential drop technique. The data recorded in terms of crack advance $\Delta a(t)$ merged with loadline displacement history $\delta(t)$ are illustrated in fig.1-2. On these selected test results (pure creep and long dwell creep-fatigue tests), it can be seen that $\Delta a(t)$ is proportional to $\delta(t)$. For the loadline displacement history, which has been considered to reflect the behaviour at high temperature of the studied material, the reference length (l_{ref}) has been introduced by Pineau et al. (2) : $\delta(t) = l_{ref}\varepsilon(t) = l_{ref} B_1 \sigma_{ref}^{n_1} t^{p_1}$ in primary creep and $\dot{\delta} = l_{ref}\dot{\varepsilon} = l_{ref} B_2 \sigma_{ref}^{n_2}$ in secondary creep, where σ_{ref} is the reference stress (3) for a material of which creep behaviour can be written like this: $\varepsilon = B_1\sigma^{n_1}t^{p_1}$ (primary creep) and $\dot{\varepsilon} = B_2\sigma^{n_2}$ (secondary creep). The fact that $\delta(t) = \kappa\, \Delta a\,(t)$ also enables us to model $\Delta a(t)$ with the same concept shown above.

MODELLING $\Delta a(t)$, $\delta(t)$, C* AND C^*_h

In some assessment procedures (4)(5), for pure creep and creep-fatigue tests with long hold time, the crack growth rate $\dot{a}$ is plotted against C* (or C^*_h). These latter loading parameters are essentially a function of $\delta(t)$. As shown earlier, both Δa and δ can be written as : $\Delta a(t) = A_a.t^{p_1}$, $\delta(t) = A_\delta.t^{p_1}$,in primary creep an $\Delta a(t) = B_a.t$, $\delta(t) = B_\delta\, t$, in secondary creep. Furthermore : $a(t)=a_0+\Delta a(t) \Rightarrow \dot{a} = A_a p_1 t^{(p_1-1)}$, hence, $\Delta a = \dot{a}\, t/p_1$ and $\delta=\kappa \dot{a}\, t/p_1$. The expression of C^*_h is (7) : $C^*_h \approx 2\frac{n_1}{n_1+1}\frac{F}{B(W-a)}\frac{\delta}{t^{p_1}}$. Substituting the last expressions to $\delta(t)$ and $a(t)$ gives respectively : $C^*_h=K_p\dot{a}\, t^{(1-p_1)}/(W'-\dot{a}\, t/p_1)$, where $K_p=2(n_1/(n_1+1))(F/B)(\kappa/p_1)$ and $W'=(W-a_0)$. For the secondary creep C* loading parameter : $C^*=K_s\dot{a}\,/(W'-\dot{a}\, t/p_1)$, where $K_s=2(n_2/(n_2+1))(F/B)\kappa$, $W'=(W-a_0)$.

It is more convenient to write $\dot{a}$ as a function of either C* or C^*_h : in primary creep $\dot{a} = W'C^*_h/[C^*_h t/p_1+K_p t^{1-p_1}]$ and in secondary creep $\dot{a} = W'C^*/[C^* t/p_1+K_s]$.

The transition time t_2 between the primary and secondary creep regimes was introduced by Riedel and Rice (6): $t_2=[(n_2p_1+1)/(n_2+1).C^*_h/C^*]^{1/(1-p_1)}$. The comparison between this quantity and the corresponding times deduced from experimental data (t_{EXP}) present some discrepancies : the t_2(h) and t_{EXP}(h) for CT86 - 14.25kN load (and CT87 - 13.25kN load) specimens are 8 (88) and 360 (1350) respectively. In fact, t_2 has been defined as the time necessary for the stress relaxation to reach the asymptotic value of the equivalent stress (7). In the following, we suggest taking the experimental values of the transition time (t_{EXP}) i.e., the time where $\dot{\delta}$ (hence $\dot{a}$) reaches its minimum value for the first time. This choice obviously induces some discontinuities in the above equations.

WORKED EXAMPLES FOR PURE CREEP TESTS

Applying the above model on the CT specimen pure creep tests, only the material parameters and κ value need to be known. For the 316L(N) at 650°C : $n_1 \approx 5.5$, $p_1 \approx 0.5$, $n_2 \approx 7$ and as can be seen in fig.1-2, $\kappa \approx 2.5$. **Fig. 3** shows the comparison between experimental and simulated $\dot{a}$ history. The simulated curves are related to experimental values of C^*_h and C^*, i.e. experimental values of δ have been put in the expression of C^*_h and C^*. The diagrams in fig.3 show the discontinuities at the transition time, whose value was imposed from experimental data. Therefore, it does not account for theoretical imposed continuities on the deformation rate. However, a good agreement is noticed between the trends of experimental and simulated curves.

LOCAL APPROACH : CREEP DAMAGE PARAMETER

One of the criticisms addressed towards the two parameter approach (C^*_h and C^*) concerns unit difference. This drawback can be avoided either by directly modelling the crack advance Δa, or by introducing a parameter which integrates the piecewise function described in primary and secondary creep regimes.(7)(8). The thesis work of D. Poquillon (8) was aimed at simulating, by finite element method, the crack growth in a 316L(N) material at 600°C for different geometries under pure creep and creep-fatigue loadings. The pure creep D damage parameter is defined incrementally as follows : $dD=A\Sigma^\alpha \varepsilon_{eq}{}^\beta d\varepsilon_{eq}$, where Σ is the maximum principle stress, ε_{eq} is the equivalent creep deformation, A, α and β are material coefficients. This simulation considers a critical damage concept : a crack extension of 50μm is allowed when the D damage at 50μm ahead of the crack tip is reached. This method requires remeshing the modelled cracked body, as the crack progresses. Due to the lack of space, this concept will not be developed further here.

GLOBAL APPROACH APPLIED TO CREEP-FATIGUE TESTS

When the dwell period under creep-fatigue conditions is large enough, it is accurate to consider the creep contribution alone in the creep-fatigue crack growth rate model. The integration scheme can be summarized as follows :

- When $t < t_{TR}$ $$\Delta a(t+\Delta t)=\int_t^{t+\Delta t}\frac{W'C^*_h}{C^*_h\dfrac{t}{p_1}+K_p t^{1-p_1}}dt \quad \text{(primary creep)}$$
- When $t > t_{TR}$ $$\Delta a(t+\Delta t)=\int_t^{t+\Delta t}\frac{W'C^*}{C^*\dfrac{t}{p_1}+K_s}dt \quad \text{(secondary creep)}$$

These expressions can be simplified in order to be calculated in a data sheet, remembering however that C^*_h and C^* depend on the value of $\Delta a(t)$.

- When $t < t_{TR}$, $$\Delta a(t+\Delta t)=\Delta a(t)+\Delta t\frac{W'C^*_h}{C^*_h\dfrac{t}{p_1}+K_p t^{1-p_1}} \quad \text{(primary creep)}$$

- When $t > t_{TR}$, $$\Delta a(t+\Delta t) = \Delta a(t) + \Delta t \frac{W'C^*}{C^* \frac{t}{p_1} + K_s}$$ (secondary creep)

In order to predict a(t) during the test, the fracture mechanics loading parameters (C^*_h and C^*) have to be calculated by a simplified method. In this text, the EMP method (7), based on reference length, has been chosen. The expressions are :

$C^*_h(\mathrm{EMP}) \approx 2\frac{n_1}{n_1+1}\frac{F}{B}\gamma B_1 \sigma_{ref}^{n_1}$ $\quad C^*(\mathrm{EMP}) = 2\frac{n_2}{n_2+1}\frac{F}{B}\gamma B_2 \sigma_{ref}^{n_2}$, where σ_{ref} is the reference stress (3) calculated in plane strain, with a Von Mises criterion and $\gamma \approx 4.5$ as reported in reference (1). K_p and K_s (unit : N/mm) can be easily calculated provided that the κ proportionality coefficient between δ and Δa is known. Fig.1-2 show that κ is approximately equal to 2.5. The results are illustrated in **fig.4**, where we also merge the experimental crack advance history. The trend is well simulated in spite of the discontinuities in $\dot{a}$. In the primary creep regime $\dot{a}$ is underestimated, which is why the slope of a(t) is very smooth. We must point out that we have never used any classical master curve correlating $\dot{a}$ and C* during the simulation.

DISCUSSION

The calculations described in this text concerning the global approach have been developed from the fact that $\delta(t) = \kappa \, \Delta a(t)$. The origin of this phenomenon may be related to either the geometrical effects : the crack extension increases the loadline displacement, as in elastic materials; or the behaviour effects : the shape of both history curves is like that on a creep deformation curve. Generally, it is considered that in the beginning of the test, the behaviour contribution is predominant and as the crack propagates, it becomes negligible compared to the geometrical contribution (2). Thus, in ref. (2) the authors doubt if the $\dot{a}$-C* correlation is meaningful in the last part of the test since C* is directly related to $\dot{a}$. Furthermore, $\dot{\delta}(t)$ increases in the last part of the tests, which can be assimilated to the tertiary creep regime. It may be necessary to model the tertiary creep at the end of the test if the creep behaviour is supposed to operate during all the test.

The transition time definition is based on the stabilization of local stresses (6). We have seen in this text that it does not fit the "global" transition time obtained experimentally. Following the definition of t_2, the specimen is considered to be in a large scale secondary creep regime locally, but it is not yet reflected in the global parameter δ. It is necessary to study, for example, the extent of the viscoplastic radius (due to secondary creep) when the global transition time is reached. In order to avoid the $\dot{a}$ discontinuity (see fig.3), the local transition time has to be consistent with the global one.

CONCLUSION

Two pure creep and two long dwell creep-fatigue crack growth tests have been carried out on 316L(N) CT specimens. Experimental data show that the creep loadline displacement is proportionnal to the crack extension. In this case, it has been demonstrated that the crack growth rate, $\dot{a}$, is a function of C^*_h (or C^*). Thus the master curves correlating $\dot{a}$ and C^* (or C^*_h) are no longer necessary. Crack growth prediction can be done by integrating a piecewise function, depending first on C^*_h then on C^*. In order to avoid the unit change problem, the local approach of fracture mechanics based on a dimensionless creep damage is also an alternative method.

The first part of discussion deals with the physical meaning of the proportionality between $\delta(t)$ and $\Delta a(t)$. There remains a question : which of crack extension (geometrical effect) and creep behaviour is the leading phenomenon which induces this fact? The second part is devoted to the last part of the $\delta(t)$ curve, where the deformation rate is increasing, whereas the creep behaviour model does not consider the tertiary stage. The theoretical transition time between large scale primary creep and large scale secondary creep does not fit with the experimental transition time obtained with the $\delta(t)$ curve.

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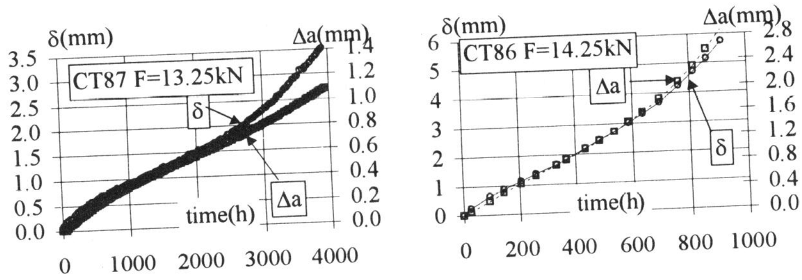

Figure 1 : δ and Δa evolutions for pure creep tests

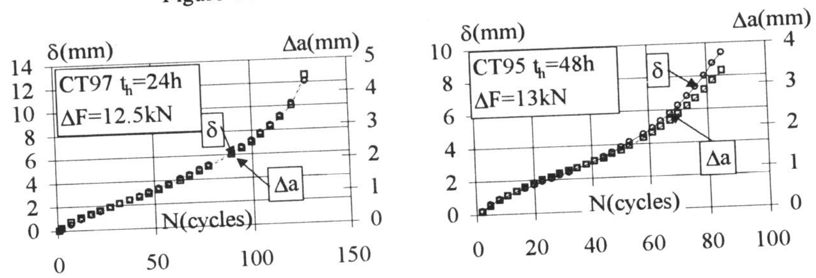

Figure 2 : δ and Δa evolutions for creep-fatigue tests

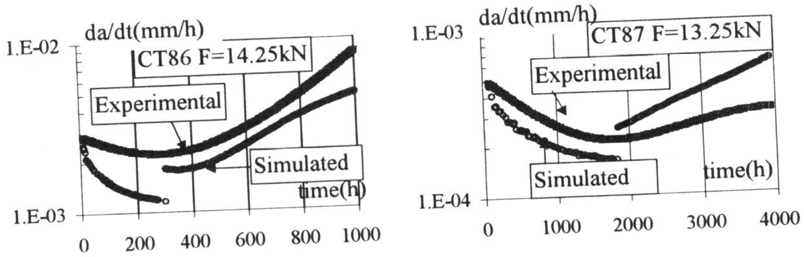

Figure 3 : experimental and simulated with C^*_h and $C^*\ \dot{a}$ history for pure creep tests

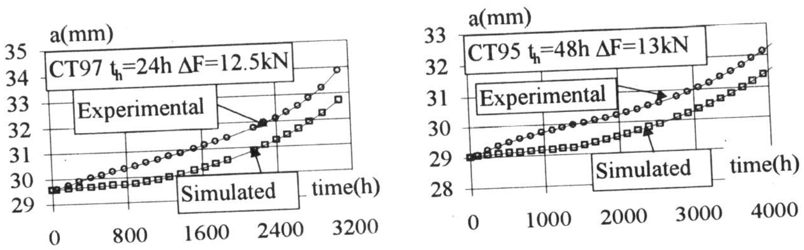

Figure 4 : experimental and predicted crack depth history for creep-fatigue tests