# CRACK INITIATION ON 316L(N) CT SPECIMENS UNDER CREEP-FATIGUE CONDITIONS

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In power plant operating at elevated temperatures, components are subjected to complex loading history including creep, fatigue and creep-fatigue effects. A practical and validated method for calculating the initiation time for pre-existing defects is needed. An attempt is made to analyse creep-fatigue tests performed both at the Ecole des Mines de Paris (EMP) and at the Commissariat à l'Energie Atomique (CEA) Saclay on 316L(N) CT specimens, by combining local and global approaches to predict crack initiation with Fracture Mechanics concepts.

## INTRODUCTION

In power plant operating at elevated temperatures, components are subjected to complex loading history including creep, fatigue and creep-fatigue effects. Test programmes have been performed both at EMP and CEA Saclay on 316L(N) CT specimens, aiming the development of a methodology for prediction of crack initiation under high temperature (600°C and 650°C) monotonic or cyclic loadings with or without hold time.

The EMP local approach (1-2) suggests that in pure creep, crack initiation occurs when the creep damage D calculated at 50µm ahead of the initial crack front reached a critical value . The damage incremental law is : $dD=A\Sigma^{\alpha}\varepsilon_{ceq}^{\beta}\, d\varepsilon_{ceq}$, where $A=2.10^{-5}$ $\alpha=2$ and $\beta=-0.5$. D (in %) indicates the creep damage $\Sigma$ is the, maximum principal stress and $\varepsilon_{ceq}$ (m/m) is the equivalent creep deformation.

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Besides, the Paris' law obtained for the 316L(N) stainless steel at 600°C and 650°C is as follows (2) : $da/dN(m/cycle)=C.\Delta K^m$, where $C=7.3.10^{-11}$, $m\approx 2.9$ are adjusted constants and $\Delta K$ in $MPa\sqrt{m}$ .

In this paper, we try to combine the mechanical notion of creep damage and the classical Paris' law in fatigue loading in order to account for the crack growth rates increase when incorporating a creep component (hold time) into the fatigue cycle.

## 2. CREEP FATIGUE EXPERIMENTAL DATA

17 (seventeen) crack initiation tests were performed (Tables 1-2) at 600°C and 650°C, on normalized CT specimens made with 316L(N) stainless steel. CEA specimens were notched with a machined tip radius of about 100µm whereas EMP specimens are precracked. Load point displacement $\delta(N)$, where N is the current cycle number, is measured by using extensometer attached to the specimens. Crack length a(N) is monitored by DC potential drop technique. The number of cycle for initiation $N_i$ is determined from a(N) data, as the cycle number necessary for the crack to grow over a critical distance d=50µm.

## 3. TRANSITION TIME - CRACK PROPAGATION REGIMES

The Riedel and Rice theory (3) gives the transition time $t_1$ definition between the successive elastic-plastic and primary creep regimes which take place in the process zone at the crack tip. For 316L(N) cyclic tests, $\Delta K^2/E$ is used rather than J contour integral for a transition time $t_{TR}$ definition: $t_{TR}=[1/(n_1+1)][\Delta K^2/(E.C^*_h)]^{1/p_1}$, where K and $C^*_h$ are fracture mechanics loading parameters and $n_1$, $p_1$ are defined by the following material laws : $\varepsilon_p=B_0\sigma^n$ (plasticity); $\varepsilon_c=B_1\sigma^{n_1}t^{p_1}$ (Primary creep).

Let $t_h$ be the hold time. A test is classified "short dwell test" when $t_h < t_{TR}$ and "long dwell test" when $t_h > t_{TR}$. In fig.1, (da/dN vs $\Delta K$) curves indicates that either creep-fatigue crack propagation curves evolve parallel to the Paris law "logarithmic line" or they present a more important slope. Figs. 2a-b clearly show that "short dwell tests" ($t_h < t_{TR}$) are located in the elastic-plastic area and follow the first trend. For "long dwell tests" ($t_h > t_{TR}$), experimental points are situated in the primary creep area in fig. 2a and b, and the crack growth rates increase more rapidly (fig. 1).

## 4. CRACK INITIATION PREDICTION IN CREEP-FATIGUE

### 4.1 Creep-Fatigue crack behaviour under short dwells

By defining the damage as a "quantity" which is 0 for a safe material and 1 at the time of failure, the damages per cycle respectively are (1/N) for continuous fatigue ; ($1/N^*$) for creep-fatigue and $D_C$ for pure creep. The damage linear cumulative rule is written : $1/N^*=1/N+D_C$ where N and N* are respectively cycle numbers in continuous fatigue and in creep-fatigue. Differentiation and arrangement of this last equation give : $(da/dN^*)=(1+ND_C)^2(da/dN)$, which shows $(1+ND_C)^2$ as an acceleration term between continuous fatigue and creep-fatigue crack growth rates. Now, the creep damage $D_C$ per cycle is defined as the ratio between the damage relative to the hold time and critical creep damage value. Thus, $D_C=\int_0^{t_h} dD / \int_0^{T_i} dD$.

Fig. 3 (1) compares calculated $D_C$ values and experimental values of ($1/N^*-1/N$) for CEA tests. There is a good agreement between creep-fatigue (CF : full symbols) and pure creep (C) results. It validates the use of the damage incremental law for the creep-fatigue tests : the acceleration term may be calculated and the initiation prediction in creep-fatigue may be made by multiplying the Paris law by this acceleration term.

## 4.2. Creep-Fatigue crack behaviour under long dwells

When $t_h \approx T_i$, the test is clearly better described as creep crack initiation test rather than a creep-fatigue test. Hence, the use of $T_i$-$C^*_h$ correlation is recommended (1-2). For hold times less than the creep initiation time one may apply a $T_i$-$C^*_h$ correlation again, by using EMP simplified formula (2), with the cumulated increase of notch opening $\delta_{ti}$ up to crack initiation.

$$C^*_{ti} \approx 2 \frac{n_1}{n_1+1} \frac{F}{B(W-a)} \frac{\delta_{ti}}{T_i^{p_1}}$$

Only EMP data sheets include long dwell tests. Unfortunately, the test with the longest hold time (CT53 - $t_h$=48h), has a peculiar low value of the load line displacement at initiation. This fact has its effect on the $C^*_{ti}$ calculation.

Fig. 4 shows the CEA and EMP experimental points of the creep-fatigue tests. Area 1 (resp. 2) includes all the points situated in the elastic-plastic domain (resp. creep domain). The arrow indicates the trend of points when the hold time increases. Moreover, the correlation line $T_i$-$C^*_h$ obtained in pure creep has been drawn. For CEA tests, the longer the hold times, the more noticeable the correlation and the closer to the $T_i$-$C^*_h$ correlation the experimental points.

For EMP long dwell (CT50 - $t_h$ = 3h) test, experimental point re-enters the scatter band of the $T_i$-$C^*_h$ correlation. CT53 ($t_h$=48h) experimental point suffers from its abnormally low $\delta_{ti}$ value.

4.3. Case of tests for which $t_{TR} < t_h < T_i$

The creep-fatigue crack growth rate is usually written like this $(da/dN)_{CF}=(da/dN)_F+(da/dN)_C$ where CF, F and C indexes respectively designate creep-fatigue, continuous fatigue and pure creep. We are concerned with $(da/dN)_C$ for which $C_h^*$ parameter is better suited and $(da/dN)_C$ may be related to $C^*_h$ (2) like this : $(da/dN)_{CF}=C\Delta K^m+B(C^*_h)^q$, where B and q are constants. $C^*_h$ (noted $C^*_{th}$) is calculated with $\delta_{avg}^{th}$ (the average notch opening increment during the dwell) : $C_{th}^* \approx 2\frac{n_1}{n_1+1}\frac{F}{B(W-a)}\frac{\delta_{avg}^{th}}{(t_h)^{p_1}}$.

4.4. The temperature effects

For creep-fatigue tests carried out at 600°C (see Table 2 CT44-45) with $t_h$=5h, both points are located in the vicinity of Paris' law line (fig. 1): hold time effect vanishes at lower temperature. Therefore, the only knowledge of Paris' law is sufficient to predict crack initiation time.

## 5.CONCLUSION

A cumulative damage model is applied in order to analyse the increase of crack growth rate when cyclic loadings include dwell periods. Knowing Paris law and creep damage model at the working temperature, crack initiation prediction is possible. Moreover, the hold time effect vanishes at lower temperature.

## REFERENCES

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TABLE 1 - EMP creep-fatigue load controlled tests at 600°C

| Specimens | ΔF(kN)) | R | a/W | $t_h$(h) | θ(°C) | $N_i$(cycles) |
|---|---|---|---|---|---|---|
| CT50 | 4.120 | 0.1 | 0.5988 | 3 | 600 | 30 |
| CT53 | 3.380 | 0.1 | 0.6025 | 48 | 600 | 6 |
| CT54 | 2.772 | 0.1 | 0.6188 | 12 | 600 | 10 |
| CT56 | 2.772 | 0.1 | 0.6156 | 1.4 | 600 | 125 |

TABLE 2 - CEA creep-fatigue load controlled tests at 600°C and 650°C

| Specimens | $F_{max}/F_{min}$(kN) | ΔF(kN) | a/W | $t_h$(h) | θ(°C) | $N_i$(cycles) |
|---|---|---|---|---|---|---|
| CT38 | 13.3/0.3 | 13 | 0.55 | 0.5 | 650 | 10 |
| CT24 | 9.8/0.2 | 9.6 | 0.55 | 0.5 | 650 | 19 |
| CT29 | 8.3/0.3 | 8 | 0.55 | 0.5 | 650 | 36 |
| CT34 | 7.3/0.3 | 7 | 0.55 | 0.5 | 650 | 40 |
| CT30 | 6.3/0.3 | 6 | 0.55 | 0.5 | 650 | 157 |
| CT40 | 6.3/0.3 | 6 | 0.55 | 1.5 | 650 | 164 |
| CT41 | 7.3/0.3 | 7 | 0.55 | 1.5 | 650 | 23 |
| CT67 | 13.2/0.2 | 13 | 0.55 | 1.5 | 650 | 8 |
| CT55 | 7.3/0.3 | 7 | 0.55 | 5 | 650 | 59 |
| CT56 | 9.8/0.2 | 9.6 | 0.55 | 5 | 650 | 9 |
| CT68 | 13.2/0.2 | 13 | 0.55 | 5 | 650 | 6 |
| CT44 | 7.3/0.3 | 7 | 0.55 | 5 | 600 | 254 |
| CT45 | 9.8/0.2 | 9.6 | 0.55 | 5 | 600 | 188 |

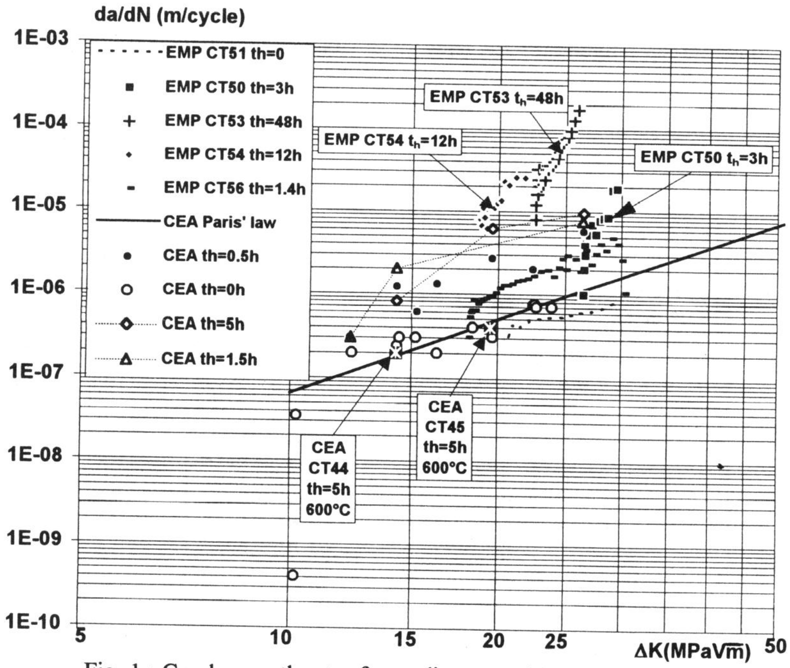


Fig. 1 : Crack growth rates for cyclic tests with hold time ($t_h$)

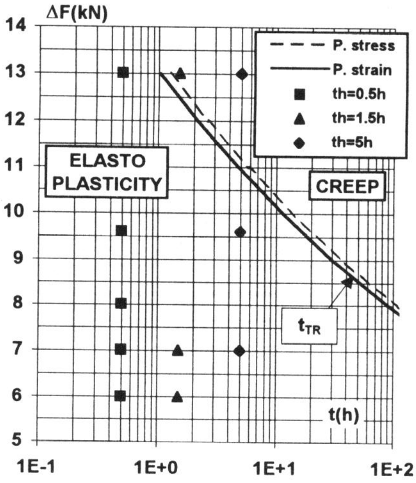


Figure 2a : Transition time and hold time under creep-fatigue for CEA tests

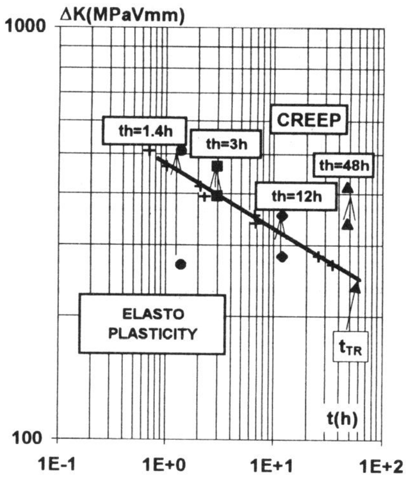


Figure 2b: Transition time and hold time under creep-fatigue for EMP tests

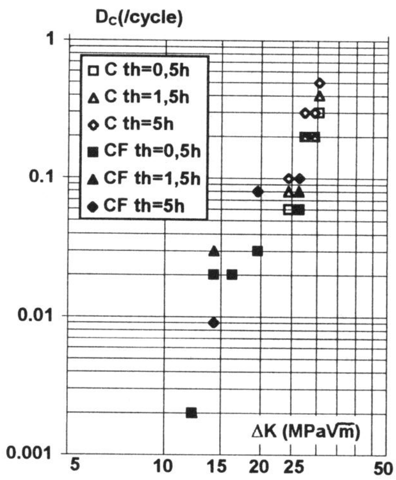


Figure 3: Evolution of $D_C$ using the incremental law of damage

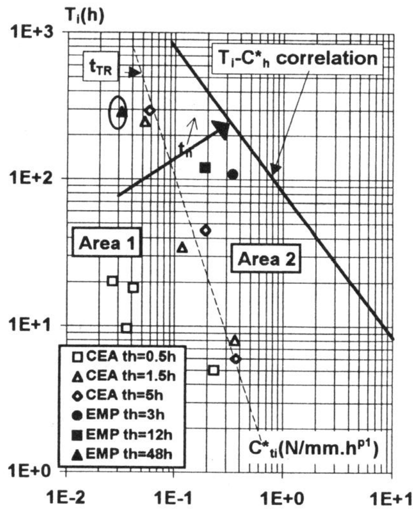


Figure 4 : $T_I$-$C^*_{ti}$ correlations