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High temperature fatigue crack growth in Alloy 718 – Effect of tensile hold times

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Abstract

The present investigation aims to clarify the mechanisms behind hold-time fatigue crack growth in Alloy 718 by using well designed tests where the crack length is carefully monitored. The results indicate that there is a significant embrittlement in a zone ahead of the crack tip during the hold-time, which is cracked open on the next load reversal. This leads to a very large cyclic contribution to the total crack length increment during a cycle, orders of magnitude larger than expected from purely cyclic tests at higher frequencies. During the hold-time follows the growth determined from pure sustained load tests, with the exception of an initial transient after the opening of the embrittled zone. An attempt to model the crack growth rate was made using a superposition model where the crack growth increments from high frequency da/dN testing and sustained load tests were added. The predictions of the total crack growth rate are generally adequate, but when the predictions of the individual contributions are scrutinized, it is obvious that the simple model does not correlate with the physical reality. Therefore both inter- and extrapolations from such a model are uncertain. Further, the test results show a decreased sustained load crack growth immediately after unloading/reloading of the crack. This transient behavior can potentially explain the reduction in crack growth rates previously explained by overload effects.

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Keywords: Fatigue crack growth; High temperature fatigue; Hold-time crack growth;
1. Introduction

The detrimental effect of tensile hold-times on the high-temperature fatigue crack growth in the Ni-base superalloys is well known, e.g. [1], and it has been shown that the behavior can be modeled relatively accurate using a superposition model where the contributions from cyclic loading and sustained load crack growth are summed over each cycle [2].

The main assumption is that the crack growth can be separated into one cyclic and one time dependent part [2] according to

\[ \Delta a_{tot}^i = \Delta a_c^i + \Delta a_{HT}^i \]  

where \( \Delta a_{tot}^i \) is the total crack extension during cycle \( i \) and \( \Delta a_c^i \) and \( \Delta a_{SL}^i \) are the contribution from the cyclic and sustained loading, respectively. The cyclic crack growth rate is conventionally described by the Paris equation

\[ \frac{da}{dN} = C \cdot (K_i)^m \Rightarrow \Delta a_c^i = C \cdot (K_i)^m \]  

where \( K_i \) is the stress intensity factor (SIF) range in cycle \( i \), and is assumed to be completely time-independent and associated only with the occurrence of a unloading–reloading event. The time dependent crack extension occurring at sustained load is assumed to follow a \( K \) dependent relationship according to

\[ \frac{da}{dt}_{HT} = A \cdot (K_{max}^n) \Rightarrow \Delta a_{HT}^i = \int_0^{t_h^i} \frac{da}{dt}_{SL} \, dt = \int_0^{t_h^i} A \cdot (K_{max,i}^n) \, dt = A \cdot (K_{max,i}^n) \cdot t_h^i \]  

where \( t_h^i \) is the hold time applied during cycle \( i \), and therefore the full expression for the crack growth during cycle \( i \) takes the form

\[ \Delta a_{tot}^i = C \cdot (K_i)^m + A \cdot (K_{max,i}^n) \cdot t_h^i \]  

When integrating the time-dependent term in Eq. (4) it is assumed that the crack growth occurs at constant \( K_{max} \). This is obviously not true if the applied load is held constant, as in the present case, but this is the assumptions typically made in analysis of hold time crack growth [2]. As part of the aim of the present study is to assess the validity of the superposition model, the same assumption is applied also here.

2. Experimental

Fatigue crack growth tests were performed on Alloy 718 bar material having a grain size of ASTM 10, using Kb-type specimens and the crack length was monitored using direct current potential drop technique. Tests, all with \( R=0 \), were performed at 550 and 650°C with hold-times of 0, 90, 2160 and 21600 s at maximum load. The frequency in the purely cyclic tests was 0.5 Hz and for consistency the ramp-up and ramp-down times in the hold-time tests were kept at 1 s each. The SIF calculated according to [3] assuming a semi-circular crack front, which was confirmed post-mortem. For a more extensive record of the material and experimental conditions refer to [4].

The parameters in the cyclic crack growth law (\( C \) and \( m \)) are obtained by fitting Eq. (2) to the data from the tests without hold-time, see Fig. 1(a), and as no pure sustained load crack growth (SLCG) tests...
were performed, the parameters in Eq. (3), \( A \) and \( n \), were obtained by regression using the \( da/dt \) data from the tests with 21600 s hold time, see Fig 1(b). It should be noted that at 650°C the maximum crack length was reached before the completion of one full cycle and the tests is in effect a pure SLCG test. The \( da/dt \) data was obtained by taking the differences in running average of time and crack length, each cycle being analyzed separately.

To evaluate the test data from the hold-time tests the values of \( (\Delta a_{i,\text{tot}}, \Delta a_{i,c}, \Delta a_{i,\text{HT}} \text{ and } \Delta K_i=K_{\text{max}}^i) \) are extracted according to Fig. 1(c). Note that the values of \( \Delta K_i \) and \( K_{\text{max}}^i \) are calculated from the final crack length from cycle \( i-1 \), that is \( \Delta K_i=\Delta K(a_{i,1}) \) using the nomenclature from Fig. 1(c). The logic is that the meaning of the analysis is: what happens when a given stress is applied to a structure containing a pre-existing crack of a given size? Consequently the SIF is based on the applied stress and the size of the existing crack, or in the case of repeated loading, on the crack size from the previous cycle. The exceptions are 550°C, 90 s hold time and 650°C 21600 s hold time. In the first case the different parts of the crack extension could not be identified as their values were in the same order as the scatter/noise, whereas in the second case less than one cycle was recorded, and hence the analysis is not applicable.

3. Results

Fig. 2 shows the results of modeling the hold-time fatigue crack growth behavior using the superposition model described by Eq. (4) based on the parameters obtained as described above. The behavior is generally fairly well predicted by the simple model, being obviously un-conservative only for the 21600 s hold-time tests at 550°C.

To investigate the behavior more closely, the individual contributions, \( \Delta a_{i,c} \) and \( \Delta a_{i,\text{HT}} \), where plotted together with the predictions made by Eqs. (2) and (3) together with the total crack extension in Fig. 3.

For the short hold-times, referring to 2160 s at 550°C and 90 s at 650°C, the behavior is generally dominated by the cyclic crack extension, which is grossly under-predicted by the parameters obtained from purely cyclic loading. The contribution from the crack growth during hold-times on the other hand is generally over-predicted. This leads to the total crack extension being relatively well predicted, although the individual components are very poorly captured.

At 21600 s at 550°C the hold-time part is better predicted, whereas the cyclic part is again under-predicted. As the total crack growth is dominated by the hold-time contribution the model performs relatively well, although it can be seen that the significant cyclic contribution pushes the model to the un-conservative side.
At 2160 s and 650°C the data indicate an initially transient behavior, indicating a threshold level at approximately 15 MPa/m. This transient is however not observed during the “pure SLCG”-test (21600 s). It is not clear whether this is a true phenomena resulting from the interaction of cyclic and sustained load or if it is an artifact from testing. The behavior appears to saturate at a level controlled by the hold-time component and the model predictions follow the same trends as for 21600 s at 550°C.

Figure 2. Result of modeling the hold-time fatigue crack growth using Eq. (4) for (a) 550°C and (b) 650°C.

Figure 3. Experimental (∅ Δa_c; • Δa_H; × Δa_total) and predicted values (— Δa_c; —— Δa_H; —— Δa_total) for tests at (a) 550°C, 2160 s hold time; (b) 550°C, 21600 s hold time; (c) 650°C, 90 s hold time; and (d) 650°C, 2160 s hold time.
Figure 4. Example of $\frac{da}{dt}$ vs $K_{\text{max}}$ from selected cycles for the specimen tested with 21600 s hold-time at 550°C, showing the initial transient in the SLCG rate.

4. Discussion

As obvious from Fig. 3, the cyclic crack growth, i.e. the crack extension occurring during the unloading–reloading event, is several orders of magnitude greater than observed from tests at 0.5 Hz without hold-time. This suggests that there is a damage occurring ahead of the crack, supposedly an oxygen-embrittled zone (OEZ) where the fracture toughness is locally reduced [5]. A steady-state situation can be proposed where the crack advances at sustained load with an OEZ ahead. When load is reduced after the hold time, the steady-state zone is still present at the tip and is cracked open upon reloading. This suggests an OEZ in the order of 0.01 to 0.1 mm depending on the combination of temperature, hold time and SIF.

The presence of an OEZ is further supported by the presence of an initial transient in $\frac{da}{dt}$ after unloading–reloading, see Fig. 4 for an example. As the OEZ is cracked open upon loading, the material ahead of the crack tip is in its un-damaged state and the observed transient is related to the development of the steady-state situation. The presence of the initial transient is also the reason for the over-prediction of the hold-time contribution at shorter hold-times, where much of the time is spent in the transient region with lower crack growth rate, in spite of the non-conservative assumption of crack growth at constant $K$.

At longer hold-times the transient makes up a smaller part of the cycle and the effect is reduced. The kinetics of the steady-state zone build-up has not been investigated more closely in the present case, but the times are observed to be in the range of one hour at 550°C and around 5 minutes at 650°C.

It should also be emphasized that the loading cycle during an actual flight cycle, including start-up, taxing, take-off, climb, cruse, landing and shut-down, is far more complex than the isothermal trapezoidal waveform used in the present test program. This can in turn have significant effects on the high temperature fatigue crack growth response of the material, see e.g. [6, 7], and requires much more complicated models, e.g. [8]. This is however out of the scope of this investigation.

It has been reported that overloads can turn off the hold time effects, e.g. [7], and it has also been shown that this effect is at least partly due to the suppression of crack growth during the hold-time following an overload [9]. The initial transients observed in the current results clearly indicate that this suppression occurs also after conventional un-loading/loading, without the application of an overload. More focus on the transient behavior may suffice to produce more accurate prediction models without complex relations from the load history taken into account.
5. Summary and conclusions

The results show that there is a significant embrittlement in a zone ahead of the crack tip during the hold-time, which is cracked open on the next load reversal. This leads to a very large cyclic contribution to the total crack length increment during a cycle, orders of magnitude larger than expected from purely cyclic tests. During the hold-time, the sustained load crack growth follows the behavior determined from pure sustained load tests, with the exception of an initial transient which is associated with the build-up to the steady-state condition after the opening of the embrittled zone. When the superposition model is applied, the predictions of the total crack growth rate are generally adequate. However, when the predictions of the individual contributions are scrutinized, it is obvious that the simple model does not correlate with the physical reality and that inter- and extrapolations are therefore very uncertain.

The main conclusion to be drawn is that dimensioning of high temperature components subjected to hold-time cycles is hazardous if the linear superposition model is used as it does not capture the physical reality of the phenomena, at least not under the more extreme conditions used in the present study. As soon as a crack starts to grow under hold-time conditions as applied here, the component life is immediately exhausted. Preferably, testing should be aimed finding the safe operating envelope where assumed cracks do not grow which will then impose restrictions on the allowable designs so that only loading conditions within the envelope is permitted.

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