CHARACTERIZING AND PREDICTING CRACK GROWTH BEHAVIOR IN ALLOYS AT ELEVATED TEMPERATURE

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ABSTRACT

It has been analytical shown in the literature that K^2/t, where K = stress intensity parameter and t = time, uniquely characterizes the stress and strain rate in the crack tip region under small scale creep conditions for materials obeying the power law creep behavior. Similarly, for large scale creep conditions, it has been shown that the C^* line integral characterizes the crack tip conditions. This paper briefly reviews these stress analyses and presents considerable crack growth rate data developed under cyclic and static loading conditions on ASTM A470 class 8 steel at 538°C and AISI 304 stainless steel at 594°C. These data clearly show that K and C^* also characterize the crack growth rate behavior at elevated temperature under conditions of small scale creep and large scale creep, respectively.

Mathematical models, proposed by the authors, for predicting and representing the influence of frequency and hold time on fatigue crack growth rate are evaluated with experimental data. Good correlations between the predicted behavior and the data were obtained. Limitations of the models are also discussed.

KEYWORDS

Creep, growth, fracture, mechanics, fatigue, stainless steel-304, cracks, frequency, steel-A470.

INTRODUCTION

Many engineering components are operated in the elevated temperature regime where creep deformation becomes a significant design consideration. To ensure the reliability of such components, the flaw tolerance under service conditions should be estimated and appropriate inspection procedure and inspection intervals established. Although linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM) methods have been developed to assess the flaw tolerance of components operated in the subcreep temperature regime, their application under thermal creep conditions can not be assumed. Additional analyses and experimental verification are needed to develop the methods for characterizing crack growth behavior in the creep regime.

In this paper, the stress analysis of cracks and experimental crack growth rate data developed at elevated temperatures are briefly reviewed to establish candidate field parameters that characterize the crack tip conditions under sustained and cyclic loading in the creep regime. Some models, recently proposed by the authors for representing the effect of frequency and hold time on the fatigue crack growth behavior at elevated temperatures, are also reviewed and evaluated.

STRESS ANALYSIS OF CRACKS AT ELEVATED TEMPERATURE

Figure 1 shows a schematic of the stress distribution and the deformation zones ahead of a crack tip in a body subjected to stress at elevated temperature [1]. At time t = 0, when the load is suddenly applied, a plastic zone forms at the crack tip. If the plastic zone is small, the stress and strain behavior in the vicinity of the crack tip (termed as the K-zone) will be characterized by the stress intensity parameter, K. With time, creep deformation will accumulate at the crack tip, but K will continue to characterize the crack tip conditions as long as significant creep deformation is restricted to a region which is small compared to the K-zone size. From a practical stand point, this small scale creep regime is important for large structures with small cracks where creep deformation occurs at the crack tip but the bulk of the body remains linear elastic. For material obeying the power law creep behavior (small scale yielding), the stress and strain as a function of distance from the crack tip, r, as well as time, t, are given by Riedel and Rice [2]

$$\sigma \;\alpha\; \left(\frac{K^2}{Ert}\right)^{\frac{1}{n+1}} \qquad (1)$$

$$\varepsilon \;\alpha\; \left(\frac{K^2}{Ert}\right)^{\frac{n}{n+1}} \cdot t \qquad (2)$$

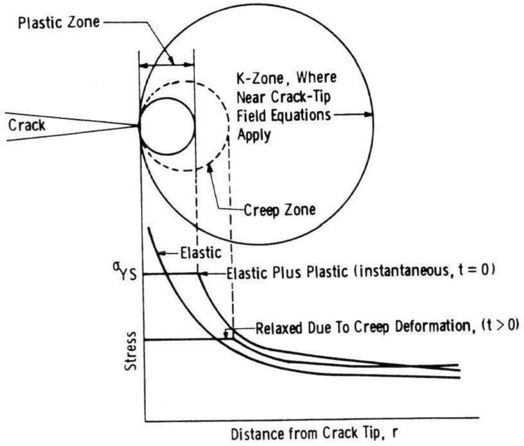

Fig. 1 The deformation zones ahead of the crack tip at elevated temperatures.

$$\dot{\varepsilon} \;\alpha\; \left(\frac{K^2}{Ert}\right)^{\frac{n}{n+1}} \qquad (3)$$

where K = applied initial stress intensity factor, E = elastic modulus, and N is the exponent in the secondary creep hardening equation, $\dot{\varepsilon} = A\sigma^n$.

When creep deformation becomes wide spread, K can no longer be used to characterize the crack tip conditions. Under this large scale creep condition, the crack tip conditions are characterized by the energy rate line integral, C^*, as follow [3]:

$$\sigma \;\alpha\; \left(\frac{C^*}{r}\right)^{\frac{1}{n+1}} \qquad (4)$$

$$\dot{\varepsilon} \;\alpha\; \left(\frac{C^*}{r}\right)^{\frac{n}{n+1}} \qquad (5)$$

For a detailed discussion of C^* and its energy rate interpretation, the readers are referred to work published earlier [1-5].

The transition time, t_1, from small scale to large scale creep behavior has also been analytically estimated by Riedel and Rice [2]:

$$t_1 = \frac{K^2}{E(n+1)C^*} \qquad (6)$$

In Equation (6), K is calculated as if the body were linear-elastic. Using Equation (6), the transition time has been calculated for ASTM grade A470 class 8 steel at 538°C (1000°F) for tension and bend geometries, Figure 2. The transition time can range from a few seconds to several thousand hours depending on the K level, geometry and crack length. Generally t_1 is larger for non-uniform stress fields, for example, bend type compared to uniform tension type loading at the same K and crack length level.

PARAMETERS FOR CHARACTERIZING CRACK GROWTH AT ELEVATED TEMPERATURE

Based on the stress analysis described in the previous section, parameters that characterize the crack growth behavior under static and cyclic loading can be identified. The data in support of these parameters is describe below.

Crack Growth Due to Static Loading

The primary focus in this section is on characterizing steady state crack growth rate, da/dt, due to creep using field parameters such as K or C^*.

The parameter which characterizes the steady state da/dt depends on two competing factors: (1) the magnitude of da/dt itself and (2) the rate at which creep deformation spreads in the specimen or the component. If the creep deformation spreads faster than the rate at which the crack grows, a situation of wide spread creep will ultimately prevail and C^* will characterize the crack growth rate. If on the other hand, the crack growth rate is faster than or equal to the rate at which creep spreads, K will characterize the crack growth rate (if the component behave linear-elastically).

The experimental correlation between C^* and da/dt was independently attempted by Landes and Begley [4] and by Nikbin, et al. [5]. The latter study was based on one specimen geometry only, but, Landes and Begley used two specimen geometries in their evaluation of the C^* parameter. They showed that the da/dt versus C^* relationship developed for discalloy at 649°C (1200°F) was only moderately dependent on the specimen geometry. More recently, the authors also demonstrated the specimen geometry independence of the da/dt versus C^* relationship by testing 304 stainless steel at 593°C (1100°F), as shown in Figure 3 [1]. These data are significant because they substantiate the use of laboratory test data for predicting the service life of cracked components.

From analytical studies, K is expected to correlate with da/dt only when the creep is restricted in a small zone. The experimental data available in the literature support the above conclusion. For example, the data on CrMoV steel [6] at 565°C (1050°F) and on 2-1/4Cr-1Mo steel [7] at 538°C (1000°F), show a lack of correlation between K and da/dt due to excessive creep. However, a good correlation between da/dt and K is shown to exist in the data of a creep resistant alloy, Udimet 700, at temperatures as high as 843°C (1500°F). This correlation is attributed to the limited creep deformation at the test temperature.

Crack Growth Under Cyclic Loading

Crack growth under cyclic loading is an important consideration in the design of elevated temperature components. Since creep deformation is a time dependent process, the extent of creep during the fatigue cycle depends on the frequency of loading and the hold time. However, the cycle duration in most rotating equipment can range from a few hours to a few hundred hours, which is most probably shorter than the transition times at the applicable temperatures and stress intensity ranges, see Figure 2. In this domain of small scale creep, where ΔK characterize the crack tip condition, ΔK should be the characterizing parameter. The validity of ΔK for characterizing fatigue crack growth rate behavior is demonstrated by the representative da/dN versus ΔK data for AISI stainless steel [9-11] and A470 class 8 steel [12] given in Figures 4 and 5, respectively. When the component or specimen is in the elastic-plastic range, the cyclic J integral, ΔJ [13,14], is the characterizing parameter. The ΔJ parameter is particularly valuable for analyzing laboratory data generated at high stress intensities with relatively small (convenient) test specimens. Figure 6 shows the data obtained from displacement

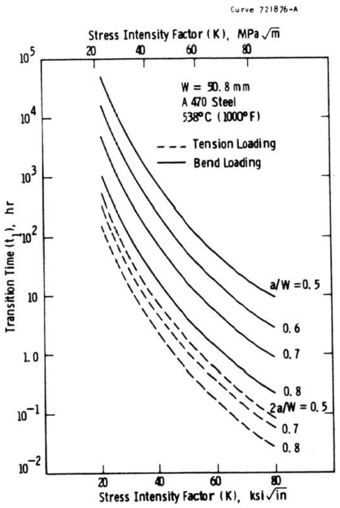

Fig. 2 Transition time as a function of K.

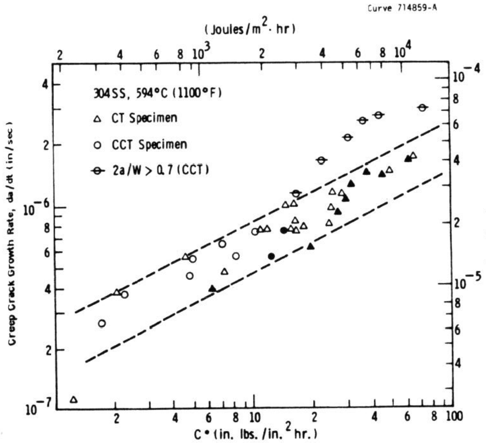

Fig. 3 Creep crack growth rate of 304 SS at 594°C as a function of C^* for two specimen geometries.

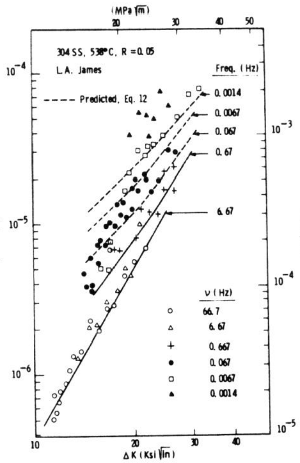

Fig. 4 Fatigue crack growth rate at various frequencies for 304 SS at 538°C.

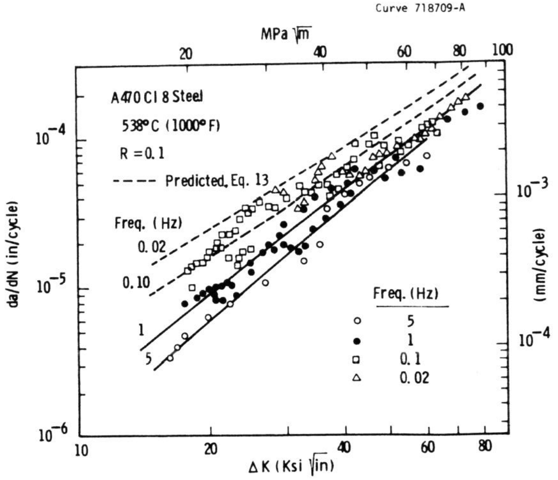

Fig. 5 Effect of frequency on the fatigue crack growth rate behavior of ASTM A470, Cl 8 steel at 538°C.

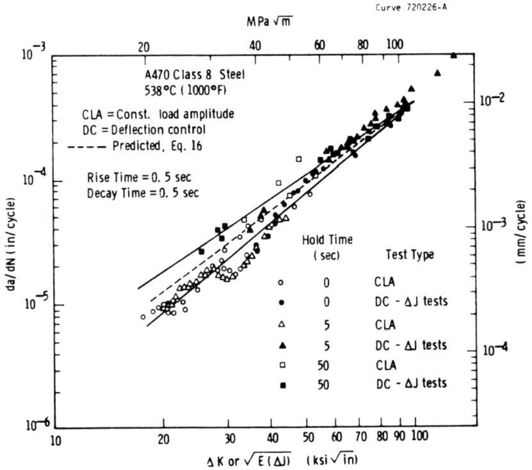

Fig. 6 Fatigue crack growth rate data for A470, class 8 steel at 538°C for various hold times.

controlled ΔJ type tests taken from our earlier work [15], also on A470 class 8 steel. These data are plotted in terms of $\sqrt{E\Delta J}$ (a form equivalent to ΔK [13,41]) to enable a direct comparison with constant load amplitude data generated in accordance with ASTM standard E-647 [17]. The two methods yield identical data within the limits of experimental scatter.

MODELS FOR REPRESENTING CRACK GROWTH BEHAVIOR AT ELEVATED TEMPERATURE

Models for representing crack growth rate behavior are needed for life prediction of components and accurate interpolation and extrapolation of experimental data. Recently, we have proposed models for representing and predicting the effect of frequency and hold time on fatigue crack growth behavior [14,15]. The effect of frequency is formulated for continuous cycling with a triangular wave shape with no hold time. The crack growth during hold time is added to the fatigue crack growth per cycle for continuous cycling to account for the hold time effect. In the subsequent discussion, these models are briefly reviewed and evaluated using the available experimental data.

Model for Characterizing the Effect of Frequency

For small scale creep conditions, the stress and strain rate at the crack tip is characterized by K^2/t. Hence, this parameter characterizes the instantaneous time rate of crack growth, Equation (7).

$$da/dt = C(K^2/t)^m \tag{7}$$

Where, C and m are material constants. Further, if crack growth rate, da/dN is plotted as a function of the time period of cycle (reciprocal of the frequency, ν), a relationship of the type shown in Figure 7 is obtained [17]. Region I ($\nu \geq \nu_o$) is the frequency independent region in which the da/dN can be described by

$$(da/dN)_o = C_o(\Delta K)^n \tag{8}$$

In Region III, the da/dN as a function of frequency can be given by the following expression.

$$\frac{da}{dN} = \frac{1}{\nu} \cdot \frac{da}{dt} \tag{9}$$

In Region II, da/dN is given by the following expression.

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_o + \int_0^{1/\nu} \frac{da}{dt}\,dt - \int_0^{1/\nu_o} \frac{da}{dt}\,dt \tag{10}$$

Substituting Equations (7) and (8) into the above equation and integrating for a triangular wave form we get

$$\frac{da}{dN} = C_o(\Delta K)^n + C_1(\Delta K)^{2m}\,(\nu^{m-1} - \nu_o^{m-1}) \tag{11}$$

If the value of ν_o can be determined either from inspection or chosen as the highest frequency for which time dependent behavior is observed in the available data, the other constants can be determined following the steps in Figure 8. These constants were determined for 304 stainless steel by using fatigue crack growth data at 6.67 and 0.667 Hz and for A470 steel using data at 5 and 1 Hz. The two equations are

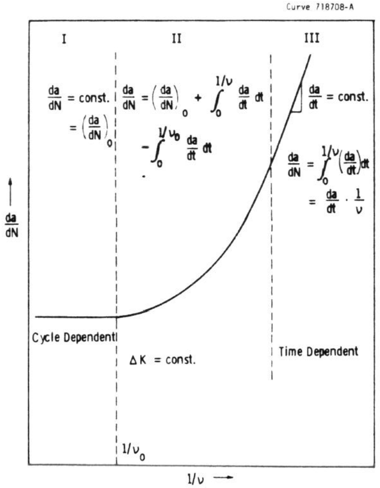

Fig. 7 Schematic representation of fatigue crack growth behavior with frequency.

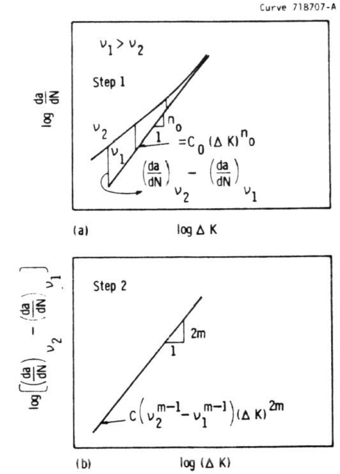

Fig. 8 Schematic representation of the steps involved in determining the constants C_o, C, n_o and m.

$$\frac{da}{dN} = 8.86 \times 10^{-10}\,(\Delta K)^{3.86} + 1.86 \times 10^{-9}\,(\nu^{-.165} - 0.731)(\Delta K)^{1.67} \text{ for 304 stainless steel} \tag{12}$$

$$\frac{da}{dN} = 6.8 \times 10^{-8}\,(\Delta K)^{2.51} + 2.2 \times 10^{-6}\,(\nu^{-.273} - .644)(\Delta K)^{1.454} \text{ for A470 steel} \tag{13}$$

where ΔK is in $MPa\sqrt{m}$ and da/dN in mm/cycle. Figures 4 and 5 show the comparison between the predicted and the observed values of crack growth rates of 304 stainless steel and A470 steel, respectively. Considering that the data have been extrapolated for several orders magnitude, the discrepancy between the predicted and observed values is small.

Model for Characterizing the Effect of Hold Time

For characterizing the effect due to hold time (t_h), the crack growth during the hold time is added to the crack growth rate due to the fatigue cycle, $(da/dN)_f$, (consisting of the loading and unloading parts) as shown in Equation (14).

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_f + \int_0^{t_h} \left(\frac{da}{dt}\right) dt \tag{14}$$

To account for the transient crack growth immediately following the rising load portion of the fatigue cycle, the da/dt during hold time is given by Equation (7) and decreases with time at a given K level. (This makes the present model considerably different from the linear super-position model [17] which does not account for the fact that steady state conditions are not achieved instantaneously following the start of the hold time period). To avoid confusion, the values of the constant C and m are replaced by C_2 and P, respectively. Combining Equations (7), (11) and (14), the following equation is obtained.

$$\frac{da}{dN} = C_o(\Delta K)^n + C_1(\Delta K)^{2m}(\nu^{m-1} - \nu_o^{m-1}) + C_2 t_h^{1-P}(\Delta K)^{2P} \qquad (15)$$

To evaluate all the constants in Equation (15), crack growth rate data are needed for one hold time in addition to the data needed for determining the constants in the first two terms of Equation (15), as discussed earlier.

Figure 6 shows the da/dN versus ΔK data for various hold times for A470 class 8 steel at 538°C. Equation (13) specifies the first two terms of Equation (15). The data for 50 seconds hold time were used to calculate the constants C_2 and P in Equation (15). Hence, the complete equation describing the frequency and hold time effects for A470 class 8 steel at 538°C (1000°F) are given by the following equation.

$$\frac{da}{dN} = 6.8 \times 10^{-8}(\Delta K)^{2.51} + 2.26 \times 10^{-6}(\nu^{-.273} - .644)(\Delta K)^{1.454} + 1.18 \times 10^{-6}(\Delta K)^{1.27}\, t_h^{0.365} \qquad (16)$$

The capability of Equation (16) to predict the fatigue crack growth rate with hold time is demonstrated in Figures 6 and 9. Note that the 1680 second hold time data taken from Reference (18) were developed after Equation (16) was derived.

Figure 10 shows the fatigue crack growth behavior of alloy 718 with and without hold time, taken from the work of Shahinian and Sadananda [17]. The no hold time and six second hold time data were used to calculate the constants in Equation (15). Since data were available at one loading rate, the first two terms in Equation (15) have been combined into one. The final equation is given below with da/dN in mm/cycle, ΔK in MPa$\sqrt{m}$ and t_h in seconds.

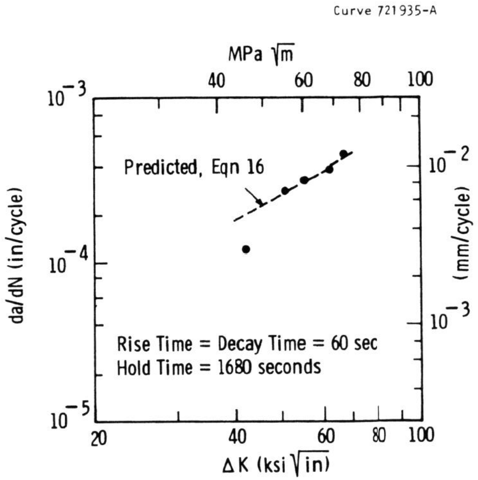

Fig. 9 Predicted and observed values of fatigue crack growth rate for A470, cl 8 steel at 538°C with 1680 seconds hold time.

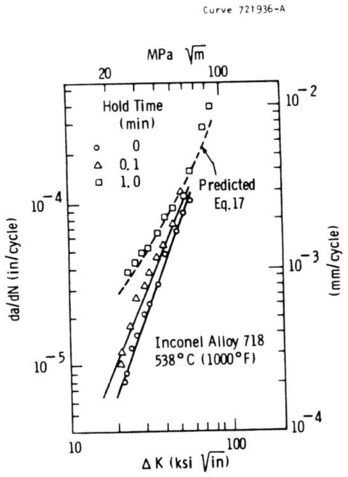

Fig. 10 Predicted and experimental crack growth rate data for fatigue with hold time.

$$\frac{da}{dN} = 5.58 \times 10^{-8}(\Delta K)^{2.6} + 3.82 \times 10^{-6}(\Delta K)^{0.738}\, t_h^{0.631} \qquad (17)$$

Equation (17) was used to predict the crack growth rate behavior for a hold time of 60 seconds. The prediction is plotted in Figure 10, along with the corresponding data. Again, there is an excellent agreement between the predicted and the observed crack growth rates. These models are semi-empirical models in which the constants obtained for a given set of environmental conditions cannot be used in a different environment. For example, in some materials it has been shown that the effect of frequency on the crack growth rate is negligible if the tests are conducted in inert atmosphere or in vacuum [19-21]. In such cases the preexponent constants in the time dependent parts of Equation (15), C_1 and C_2, will be zero. Hence, the model has the provision to model such behavior, provided, the constants are determined separately for the two environments based on actual data.

The assumption that da/dt is characterized by K^2/t does not imply that the crack growth mechanism is creep dominated. K^2/t, by the virtue of characterizing the crack tip conditions in the presence of creep, can be expected to characterize da/dt even if the time dependent behavior is due to corrosion. However, when the environmental effects dominate to the extent that the crack tip stress is no longer important in determining the crack growth rate, additional terms will be required in the model to account for the phenomenon. This, and other limitations of the model are listed below.

Limitations of the Model

The proposed models for characterizing frequency and hold time effects are in their preliminary stages of verification. More extensive data covering slower frequencies and longer hold times are needed for more rigorous evaluations of the models. Numerical studies should be performed to verify the small scale creep solutions for cracked bodies on which the model relies heavily. Hence, appropriate modifications to the model are possible as more data and analysis become available. In their present form, some limitations apply to the models. These are listed below.

(1) The model is valid where the mechanisms of crack growth is a mixture of creep and environment. If environmental effects dominate the crack growth mechanism to the extent that da/dt is independent of crack tip stress, additional terms may have to be added in Equation (7) to get good fits to the data.

(2) The model has so far been developed and verified for small scale creep conditions only. Some ideas on how it can be extended to large scale creep conditions have been discussed earlier [15].

(3) The model does not account for wave form effects; hence, it should not be used to predict the crack growth behavior of a given wave form using data generated on another wave form without verification testing.

SUMMARY AND CONCLUSIONS

This paper discusses near-crack tip field parameters that characterize crack growth due to sustained and cyclic loading in the presence of creep deformation. Considerable crack growth rate data are included to substantiate the choice of these field parameters. Using these field parameters, crack growth rate data generated on small specimens in the laboratory can be used for making life predictions of structures. Models for representing and predicting frequency and hold time effects are also discussed. The following conclusions can be derived from this paper.

(1) When creep deformation is restricted to a small region at the crack tip, stress intensity parameter, K, characterizes the crack tip stress, strain and strain rate behavior with time. When creep deformation is widespread, the crack tip conditions are characterized by the energy rate line integral C^*.

(2) According to the data presented in this paper, K also characterizes the crack growth behavior under sustained and cyclic loading at elevated temperature for small scale creep conditions. For large scale creep conditions, C^* characterizes the crack growth behavior under sustained loading.

(3) The proposed models for representing the frequency (loading rate) and hold time behavior have been shown to represent and predict the crack growth behavior accurately. However, more experimental verification of the models is recommended.

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