CREEP-FATIGUE CRACK GROWTH IN POWER-PLANT MATERIALS AND COMPONENTS

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ABSTRACT

The stress-time-temperature history experienced by header, turbine casings, turbine rotors and pipes in conventional power-plants necessitate the consideration of creep deformation and damage in design and remaining life prediction. In this paper, some of the recent developments in predicting crack growth behavior under creep-fatigue conditions using the concepts of time-dependent fracture mechanics are reviewed. While substantial progress has been made in this field, several gaps in the technology still exist. The paper concludes with a description of the limitations of this approach and where future research must be focussed.

KEYWORDS

fatigue, creep, steels, crack growth, C_t-parameter, weldments, thermal-fatigue

INTRODUCTION AND BACKGROUND

Extending the life of power-plant and chemical reactor pressure vessels by 20 to 40 years beyond their original design life of 30 to 40 years is multibillion dollar consideration. High temperature components are subjected to degradation as a result of prolonged exposure to stress and temperature. Linear and nonlinear fracture mechanics approaches are central to the management of risk of operating such components beyond their original design life. As an example, Fig. 1a shows cracks that were found in the interior of a steam header during an inspection after approximately 25 years of operation, at a maximum service temperature of 538°C. Figure 1b shows the results of a 3-d elastic finite element analysis model of a header similar to the one in Fig. 1a through a complete operating cycle which includes a cold-start, steady-state operation and a shut-down. The stress-time behavior of the various critical points in the interior of the header where service cracks have been found are shown schematically. It is obvious from these stress histories as well as from the cracks seen in Fig. 1a that creep-fatigue crack growth is a major concern in these components.

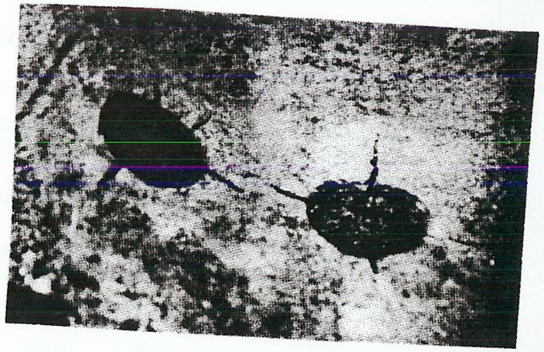


Fig. 1a - Picture of the interior surface of a steam header after service for 25 years at about 538°C.

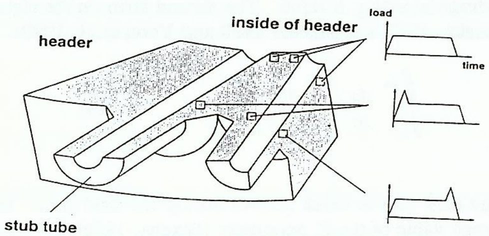


Fig. 1b - A section of a steam header and simplified fatigue loading waveforms at various critical location on the header (Yoon et al., 1993).

Table 1 shows a list of high temperature components and materials used in their construction in conventional power-plants where creep-fatigue crack growth is a major concern. Several of these components contain weldments in their original construction or are repaired by welding during service. In the latter case, expected life subsequent to welding is an important concern. The deformation characteristics of the weld metal and the crack growth resistance of the base metal/weld metal interface can be quite different from the original base metal and thus pose additional challenges in dealing with this already complex problem.

Table 1 - List of power-plant components, their typical service temperatures and the materials used in their construction.

Components	Materials Used	Service Temperature °C
Steam Turbine Rotors	1 Cr - 1Mo - 0.25V Steel	538
Turbine Casings	2.25Cr - 1Mo Steel, Cast repair weldments	538 - 565
Steam Headers	2.25Cr - 1Mo Steel 1.25Cr - 0.5Mo Steel weldments	538 - 565
Valves and Nozzles	2.25Cr-1Mo Steel 304, 316 SS	538 - 565
Steam Pipes	2.25Cr - Mo Steel 1.25Cr - 0.5Mo Steel weldments	538 - 565

Table 2 lists the considerations in predicting the long-term high temperature performance of elevated temperature components. If we critically examine the service environment and the materials used in fabricating the header, all factors listed in Table 2 can be considered relevant. However, only a subset of the factors listed dominate the cracking behavior in the component, making the analysis tractable.

In this paper, recent advances in the concepts of time-dependent fracture mechanics (TDFM) and materials test method developments for characterizing fatigue crack growth rate (FCGR) at elevated temperature and for predicting design and remaining life are briefly reviewed and several areas that need further research are also highlighted.

TDFM CONCEPTS FOR CHARACTERIZING FCGR AT ELEVATED TEMPERATURES

There are several questions about the validity of a linear-elastic parameter such as ΔK for characterizing fatigue crack growth rate in the presence of significant creep deformation (Saxena, 1988 and Kuwabara et.al. 1988). This is due to the presence of time-dependent creep strains which become more significant at lower test frequencies and also due to lower yield strength at elevated temperature promoting significant plasticity. This is particularly the case for the creep-ductile materials such as Cr-Mo, Cr-Mo-V and austenitic stainless steels widely used in the power-plant components. Creep-ductile materials are formally defined as ones which the time-dependent crack growth at elevated temperature is accompanied by substantial creep deformation. In these materials, creep effects dominate the crack growth behavior with the contribution of the environment is only secondary (Saxena, 1991).

Table 2 - Considerations in predicting crack growth life in high temperature components

- Transients and steady-state thermal stresses
- Hold times and cyclic stresses due to external loading in fracture critical locations
- Environmental effects (oxidation)
- Creep deformation (primary, secondary and tertiary) and rupture
- Varying material properties due to temperature gradients
- Material property gradients around welded joints
- Complex crack geometries
- Load interaction effects
- In-service degradation of material properties

Cyclic J-Integral, ΔJ

The ΔJ parameter (Dowling and Begley, 1976 and Dowling, 1977), which is the cyclic analog of Rice's J-integral (Rice, 1968), is relevant for characterizing high temperature fatigue crack growth behavior at high frequencies where the dominant nonlinearity in stress-strain behavior is due to cyclic plasticity at the crack tip. For materials in which the stress and strain ranges, $\Delta\sigma$ and $\Delta\epsilon$ respectively, are related by the following relationship.

$$\Delta\epsilon = \frac{\Delta\sigma}{E} + D'\left(\frac{\Delta\sigma}{2\sigma^{c}_{ys}}\right)^{m'} \qquad (1)$$

ΔJ can be defined as a path-independent integral (Lamba, 1975). D' and m' are regression constants relating $\Delta\sigma$ and $\Delta\epsilon$ and σ^{c}_{ys} is the cyclic yield strength of the material. The method of estimating ΔJ for test specimens and for components are described elsewhere in the literature (Dowling and Begley, 1976, and Dowling, 1977, and Saxena, 1993) and will not be repeated here. At slow loading frequencies or for waveforms involving significant hold times, creep deformation becomes important.

Creep Constitutive Equation

The uniaxial version of the most commonly used creep constitutive law to describe the elastic, primary creep and secondary creep deformation for power-plant materials is as follows:

$$\dot{\epsilon} = \frac{\dot{\sigma}}{E} + A_1\epsilon^{-p}\,\sigma^{n_1(1+p)} + A\sigma^{n} \qquad (2)$$

where, dots denote derivatives with time, A_1, p and n_1 are parameters relating to the materials primary creep behavior, A and n are the secondary creep constants and E is the elastic modulus.

Creep-Fatigue Crack Growth Model for Waveform with Hold Times

If we first consider trapezoidal loading waveforms which can be partitioned into a loading/unloading part and the part involving the hold time, the overall fatigue crack growth rate, da/dN, can be written as a linear superposition.

$$\frac{da}{dN} = c_1(\Delta J)^{\gamma} + \int_{o}^{t_h}\frac{da}{dt}dt \qquad (3)$$

where, c_1 and γ are regression constants obtained from fast-frequency (~1Hz) fatigue crack growth data and da/dt is time rate of crack growth during the hold time and t_h is the hold period. The above equation assumes that the loading/unloading is rapid. The second term on the right hand side can be written as (Saxena and Gieseke, 1987 and Saxena, 1993 and Yoon et.al, 1993)

$$\int_{o}^{t_h}\frac{da}{dt} = \left(\frac{da}{dt}\right)_{avg} t_h \qquad (4)$$

where, $(da/dt)_{avg}$ is the average time rate of crack growth during the hold time. In the next step, $(da/dt)_{avg}$ is related to the average value of the C_t parameter (Saxena, 1986), $(C_t)_{avg}$ as follows:

$$(da/dt)_{avg} = b(C_t)^{q}_{avg} \qquad (5)$$

Thus, combining equations (3), (4), and (5) we get,

$$\frac{da}{dN} = c_1(\Delta J)^{\gamma} + b t_h (C_t)^{q}_{avg} \qquad (6)$$

where, b and q are regression constants which can be obtained from fatigue crack growth data obtained from tests conducted with hold time.

It is necessary to point out that even though the load is constant during the hold period and the crack size does not change appreciably during each cycle, the value of C_t is very dependent on time because the stresses in the crack tip region relax and are redistributed due to creep deformation. As mentioned in earlier references (Saxena, 1991, 1993), C_t is able to accommodate this variation and that is the reason why it is necessary to represent the value of C_t by its average value during the hold time. An alternate approach can also be to assume that the instantaneous value of da/dt is related to the instantaneous value of C_t such as in the case of creep crack growth (Saxena, 1986, 1991).

Making that substitution in the relationship between $(da/dt)_{avg}$ and $(C_t)_{avg}$, an equation which is functionally the same as equation (5) is derived (Yoon et.al, 1993). Thus, either approach leads to the same result. This approach has the further advantage of asymptotically reducing to the approach for creep crack growth for long hold times. Also, for small values of the hold time, the time-dependent component becomes negligible in equation (6), as one would intuitively expect.

The above method of relating $(da/dt)_{avg}$ to $(C_t)_{avg}$ during the hold time is an evolutionary product of several other earlier attempts. The first available evidence of this approach was in the work of Jaske and Begley (1978) and that of Taira et. al (1979), Saxena et. al (1981). Others such as Nishida and Webster (1990) have also proposed a similar approach. The other approaches, with the exception of Saxena et. al (1981) which used the C(t) integral of Bassani et.al. (1981), used C^*-integral (called J^* in the Japanese literature) to characterize the crack growth rate during the hold time. Strictly, the C^*-integral does not account for crack tip stress redistribution which occurs immediately following the load application. However, if the value of C^* is calculated from measured deflection rate, the effects of stress-redistribution are included as explained in the earlier papers (Saxena, 1993). On the other hand, the C(t) integral does characterize stress redistribution but cannot be measured at the loading pins. The problem with C^* is realized when it is calculated in components when the effects of ignoring the contribution of stress redistribution is very important. The $(C_t)_{avg}$ approach remedies this problem and also with C(t) integral as described in the subsequent discussion.

Methods of Determining $(C_t)_{avg}$

Methods of determining $(C_t)_{avg}$ include (i) those that are more suitable for test specimens in which both load and load-line deflection behavior with time are measured and (ii) those that are more suitable for cracked components in which the deflection rates must be analytically predicted. for test specimens in small-scale creep, $(C_t)_{avg}$ can be approximately obtained from the following equation (Yoon et.al., 1992):

$$(C_t)_{avg} \approx \frac{\Delta P \ \Delta V_c}{BWt_h} \frac{F'}{F} \qquad (7)$$

where ΔP = applied load range, ΔV_c = change in deflection during the hold time due to creep, B = specimen thickness, W = width, F = K - calibration factor = $(K/P)BW^{1/2}$, F' = dF/d(a/w). If small-scale creep conditions cannot be assured, appropriate correction in the methods for estimating $(C_t)_{avg}$ can be made as described in earlier references (Yoon et.al. 1992, 1993, Saxena 1993). Note that if the deflection range ΔV_c is measured, no other creep constants are needed to estimate $(C_t)_{avg}$. The information about the creep behavior is embedded in this measurement.

Methods for estimating $(C_t)_{avg}$ in components rely on the creep constants for estimating the value of ΔV_c. Equations have been developed to account for the influence of elastic behavior, instantaneous cyclic plasticity and secondary creep (Yoon et.al. 1992) in the estimation of $(C_t)_{avg}$ for small-scale creep. Adefris et.al. (1994) have modified the expressions to also include the contribution of primary creep. For details of this estimation method, the readers are referred to an earlier review (Saxena, 1993).

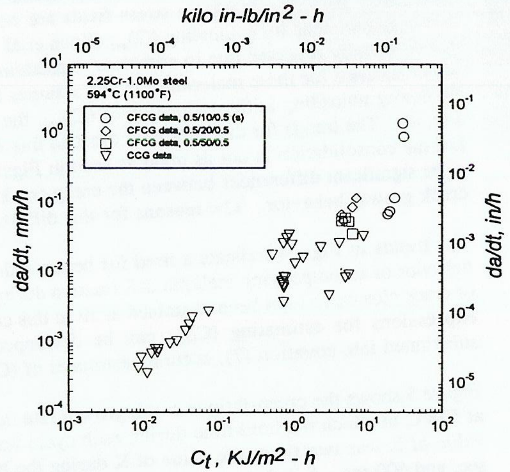
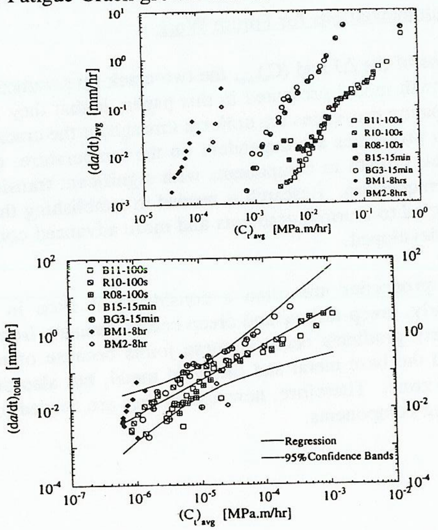


Fig. 3 - Creep-Fatigue crack growth behavior of 2.25Cr-1Mo steel at different hold times and creep crack growth rate data (Grover, 1993).

Fig 4 - Creep-Fatigue Crack growth data for 1Cr-1Mo-0.25V steel at 538°C for various hold times.



(a) $(C_t)_{avg}$ estimated assuming full reinstatement of crack tip fields following unloading and

(b) assuming no reinstatement of crack tip fields after unloading (Adefris 1993).

time. Thus, only partial reversal of creep strains by cyclic plasticity occurred during unloading. Essentially then, the crack tip stress fields are not reinstated during each cycle. Therefore, the earlier expressions for estimating $(C_t)_{avg}$ (Yoon et.al. 1992, 1993) which assume that the creep strains are essentially reversed due to complete reinstatement of the crack tip field during each unloading is not accurate for these materials. If one assumes that no creep strain reversal occurs at the crack tip during unloading in the estimation of $(C_t)_{avg}$, the data of Fig. 4a is transformed to one shown in Fig. 4b. The trends for different hold times in this figure appear to collapse better than in Fig. 4a, but the consolidation is not as good as seen in Figs. 2 and 3 for other materials. There also seem to be significant differences between the creep crack growth (CCG) behavior and the creep-fatigue crack growth behavior. The reasons for this difference are no clear.

The trends in Figs. 4 indicate a need for better understanding of the crack tip phenomena and the behavior of accompanying inelastic deformation during creep-fatigue loading. For example, the role of crack closure has not been examined at all in this context. Only after such studies, more accurate expressions for estimating $(C_t)_{avg}$ can be developed. Never-the-less, if ΔV_c is measured and substituted into equation (7), accurate estimates of $(C_t)_{avg}$ can be obtained in test specimens.

Figure 5 shows the creep-fatigue crack growth rate data from experiments on 1.25Cr - .5Mo Steel at 538°C in which the hold-time during each cycle was preceded by a tensile over-load. The peak value of K was two times the value of K during the hold time. Hold times used were, 10 sec, 98 sec, and 600 sec. A definite increase in the da/dt value for the short hold time of 10 sec as a result of overload was observed when compared to data for the condition of no overload. As the hold time increases, the influence of the overload progressively decreases.

Current Limitations and Recommendations for Future Work

One of the important limitations of the ΔJ and $(C_t)_{avg}$, the two crack tip parameters which are central to the creep-fatigue crack growth model presented in this paper, is that they are strictly valid for conditions in which the deformation properties are uniform throughout the cracked body. Since the cyclic plasticity and the creep properties are dependent on the temperature, the validity of these parameters for predicting crack growth in components with significant transient and steady-state temperature gradients is an open question. Research is needed in establishing the practical limits of these concepts for bodies subjected to thermal gradients and more advanced concepts which do not have such limitations must be developed.

In homogeneous deformation properties are often a consideration even in isothermal bodies containing weldments. Frequently, creep-fatigue and creep cracks emanate from welded joints. It is well documented that property gradients occur at these joints because of not only dissimilar deformation properties between the base metal and the weld metal, but also due microstructural gradients along the heat affected zone. Therefore, new approaches are needed to address cracking in weldments in high temperature components.

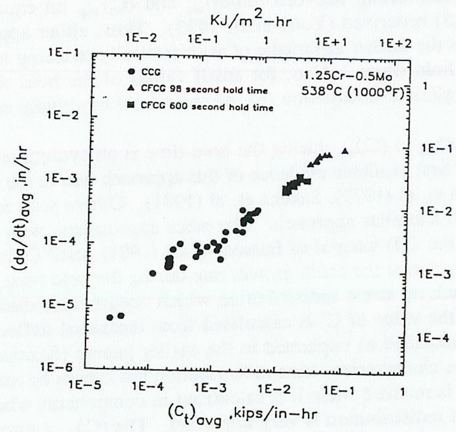


Fig. 2a - Comparison between creep-fatigue crack growth rate data in terms of measured $(C_t)_{avg}$.

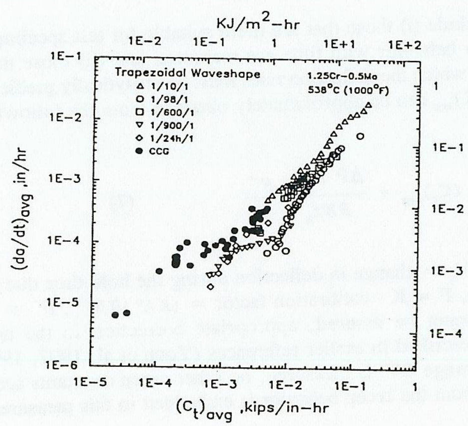


Fig. 2b - The same data as in part (a) but also including additional data for hold times of 10 sec and 24 hours with calculated values of $(C_t)_{avg}$ (Yoon et al., 1993).

Experimental Methods for Characterizing Creep-Fatigue Crack Growth

Two methods have been used to obtain creep-fatigue crack growth rate data. The first is a traditional fracture mechanics method based on testing compact type specimens which are first heated to the test temperature and subjected to cyclic loading under load-control conditions. The loading waveform, frequency and the load ratio are pre-selected and specified for the test. The load-line displacement during the entire loading cycle is measured and the crack size is measured by the electric potential method (Yoon et.al. 1992, 1993). This method yields satisfactory results provided linear-elastic conditions can be maintained in the specimens. Incremental creep and plastic deformation can accumulate during each cycle and eventually the dominance of linear-elastic conditions cannot be assured. In a variation of this test method which circumvents the above problem, the specimen is subjected to controlled load-line displacement or the crack-mouth displacement condition, while the load is measured as the response variable (Saxena et.al. 1981). Since the displacement is forced to the specified minimum value at the end of each cycle, no residual deformation accumulates, avoiding failure due to ratcheting deformation. However, during this test, the specimen undergoes significant compressive loads. Therefore, the design of loading grips and fixtures is quite different from the set-up for load-controlled testing.

The second method used for generating creep-fatigue crack growth data has been largely through the efforts of Japanese researchers (Ohtani et.al. 1988, Kuwabara et.al. 1988, Ohji, 1986). In this method, hollow cylindrical specimens of 10 to 13 mm external diameter containing cracks are axially loaded under displacement or stress controlled conditions. Crack size is monitored using electric potential technique. Due to their small sizes, the data from these specimens must mostly be in the extensive creep regime. The crack growth rate per cycle, da/dN is correlated with the ΔJ_c parameter which is identical $(C_t)_{avg}$ for extensive creep conditions [Saxena, 1993].

Trends in Creep-Fatigue Crack Growth Data

Figure 2a shows the creep-fatigue crack growth rate data for 1.25Cr - 0.5Mo steel (Yoon et.al. 1993) with hold times of 98 sec, 600 sec and also including the creep crack growth rate data. In all these creep-fatigue experiments, the displacement range during each cycle was measured and equation (7) was used to estimate $(C_t)_{avg}$. In the creep crack growth experiments, the deflection was continuously monitored also. All crack growth rate data appear to fall into a common trend indicating that $(C_t)_{avg}$ uniquely correlates the creep-fatigue crack growth rate behavior during hold time. In Fig. 2b, additional data for hold times of 10 sec, 900 sec, and 24 hours is also included. In these experiments, $(C_t)_{avg}$ is calculated using the primary and secondary creep constants of the material because load-line deflection rates were not available. These data also nicely collapse into the same trend. Similar trends were also observed for 2.25Cr - 1Mo steel in experiments performed by Grover et. al. (1995) as shown in Fig. 3.

Adefris et.al. (1993) performed creep-fatigue experiments on 1Cr - 1Mo - 0.25V steel at 538°C under hold times of 100 sec, 15 minutes and 8 hr; the results from these experiments are shown in Fig 4a. In these experiments, reliable load-line displacements were not available due to experimental difficulties, therefore, the $(C_t)_{avg}$ had to be calculated. The nice and unique trends obtained in the results of Figs. 2 and 3 were not observed for this material. It was shown be finite element analysis, that in these experiments, the creep zone during each hold time extended beyond the cyclic plastic

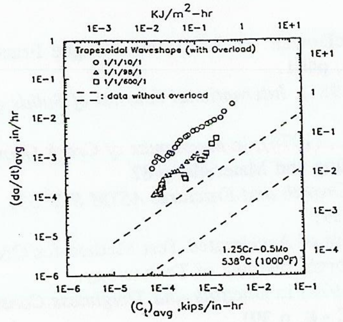


Fig. 5 - Creep-Fatigue crack growth rate behavior with various hold times for waveforms with a hold time following a tensil overload in 1.25Cr-0.5M0 steel at 538°C (Yoon et al., 1993).

No standard creep-fatigue crack growth test method is currently available. The methods discussed in this paper represent a good beginning in that direction. However, these methods suffer from several shortcomings which must be addressed before the procedure can become routinely available to engineers. A major limitation is the lack of reliable high temperature extensometry with the required resolution. A resolution for measuring deflection changes on the order of 10^{-4}mm at high temperatures along the load-line is needed for creep-fatigue crack growth testing. The capacitance gage used in our laboratory can achieve these resolutions under the best of conditions not with a high degree of reliability. Also, creative specimen designs with more secure seating of these gages are needed because the gage seating is extremely critical in cyclic loading experiments. Other experimental limitations include lack of studies which compare creep-fatigue crack growth data obtained under conditions of deflection control and those of load-control. Several transient crack growth responses have been observed during creep-fatigue testing (Saxena, 1993) even under simple loading waveforms involving hold time. Some of these transients may be caused by residual inelastic deformation in the crack tip wake region, therefore, a good understanding of the crack closure behavior may hold the key to addressing these phenomena. However, such studies have never been attempted. Since overloads are frequently encountered during transient thermal loading which is characteristic of power-plant equipment, a good understanding of the transient crack growth phenomena is very important to accurately predict the effect of overload.

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