Recent Advances in Elevated Temperature Crack Growth and Models for Life Prediction

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ABSTRACT

This paper summarizes the recent developments in the field of time-dependent fracture mechanics over the past few years. The state of understanding in this area is now at the same level as elastic-plastic fracture mechanics. The important developments and their applications are described in this paper.

KEYWORDS

Creep, Cracks, J-Integral, C^*-Integral, C_t, Fatigue

INTRODUCTION

Critical gas and steam turbine, power-plant boiler and petro-chemical reactor components which operate at elevated temperature tend to develop cracks during the service life. Some components have crack like defects even at the time they go into service which can grow and cause failure. Some examples of major failures in the power industry involving elevated temperature components where creep was a major contributing factor include turbine rotors (Kramer and Randolph, 1976) and steam pipes. These failures resulted in millions of lost dollars in down time and repair costs and, in some cases, also loss of human lives. Thus, crack growth under elevated temperature, creep conditions is a major industrial problem.

Further impetus for studying elevated temperature crack growth comes from the need to assess the remaining life of components which have been in service and are approaching their originally predicted design life. More and more operators of equipment are turning to a retirement-for-cause (RFC) philosophy rather than to rely on life predictions made several years ago with concepts which are now out-dated (Harris et al., 1980; Saxena et al. 1986).

Failures due to creep can be classified either as resulting from widespread or bulk damage, or resulting from localized damage. The structural components which are vulnerable to bulk damage are subjected to uniform loading and uniform temperature distribution during service, for example, thin wall pipes. The thin life of such a component can be estimated from creep rupture data. On the other hand, components which are subjected to stress and temperature gradients (typical of thick section components) will not fail by creep rupture. It is more likely that at the end of the predicted creep rupture life, a crack develops at the critical location which propagates and ultimately causes failure. Thus, crack growth is an important part of a component's overall life.

In this paper, the concepts of time dependent fracture mechanics (TDFM) for characterizing elevated temperature crack growth behavior and their role in life prediction are briefly reviewed. No attempt is made to summarize developments in the methods for predicting creep rupture which is broad enough by itself to warrant a separate review.

ADVANCES IN TIME-DEPENDENT FRACTURE MECHANICS (TDFM) CONCEPTS

Crack Tip Stress Analysis

The difference between the crack tip stress and strain fields of bodies loaded in the creep and subcreep temperature regime occurs due to the presence of time dependent strains in the creep regime. The accumulated strain in front of a stationary crack tip changes continuously and the crack tip stress can also vary with time depending on whether or not steady-state conditions have been reached.

The levels of creep deformation under which creep crack growth can occur include the small-scale-creep (SSC) region, the tran-sition creep region and the extensive creep region. Under SSC, the creep zone is small in comparison to the size of the body and the crack size and its growth is constrained by the surrounding elastic material. Under extensive creep conditions, the creep zone engulfs the entire ligament. The transition creep region is the intermediate condition. These regions are analogous to the small-scale-yielding, the elastic-plastic and fully plastic conditions, respectively, encountered in the sub-creep temperature regimes. In addition to the above, the picture at elevated temperature is further complicated when primary and tertiary creep deformations occur either by themselves or in conjunction with elastic and/or secondary creep deformations. Fortunately, following the pioneering work of Landes and Begley (1976) which led to the discovery of C*, the crack tip stress fields for a variety of creep deformation laws have been worked out (Riedel and Rice, 1980; Riedel, 1981, Riedel and Detempel, 1987; Ehlers and Riedel, 1981, Ohji et al. 1979). In general, we can express the amplitude of the Hutchinson, Rice and Rosengren (HRR) (Hutchinson, 1968; Rice and Rosengren, 1968) crack tip stress fields by the following equation.

$$\sigma_{ij} = \left[\frac{C(t)}{B I_\gamma r} \right]^{\frac{1}{1+\gamma}} \tilde{\sigma}_{ij}(\theta,\gamma) \qquad (1)$$

Here, B and γ are treated as generic material constants whose values depend on the dominant mechanism of creep deformation operating in the crack tip region. For example, for power-law creep B=A and γ=n; for primary creep $B=A_1(1+p)$ and $\gamma=n_1$. A, n, p, A_1 n_1 are material constants in the respective creep deformation equations given in Table 1. I_γ is a nondimensional constant which depends on γ and ranges between 3.8 and 6.3 for a range of γ values (Shih, 1983). $\tilde{\sigma}_{ij}(\theta,\gamma)$ is an angular function and r=distance from the crack tip. The expressions for extimating C(t) for several creep deformation laws are given in Table 1. Note that for extensive power-law creep $C(t)=C^*$. There is an abundance of experimental data which show that under these conditions C^* characterizes the creep crack growth behavior (Saxena, 1980).

Since C(t) uniquely relates to the amplitude of the crack tip stress fields for a variety of creep deformation laws, it is an attractive candidate crack tip parameter for characterizing creep crack growth for other than just the conditions for which it is equal to C^*. However, there are two major shortcomings of this approach. First, C(t) cannot be measured at the loading pins of the test specimens except for the two very special conditions of extensive power-law creep and the extensive primary creep shown in Table 1 (Saxena, 1988). Under these conditions, C(t) is also equal to the stress-power dissipation rate (U^*) in the cracked body. For extensive power-law creep, this relationship is given by (Landes and Begley, 1976)

$$C(t) = C^* = -\frac{1}{B}\frac{dU^*}{da} \qquad (2)$$

where, B = thickness of the specimen. However, under small-scale and transition creep conditions $C(t) \neq -1/B\,(dU^*/da)$.

The second shortcoming results from the question about the dominance of the HRR fields for growing cracks. It has been experimentally (Saxena et al., 1984) and numerically (Hawk and Bassani, 1986) shown that this limitation is not important in the extensive creep regime when crack velocities are low and the HRR fields essentially dominate over large distances ahead of the crack tip. Recent numerical results (Hawk and Bassani, 1986), reproduced in Fig. 1, have shown that in SSC, the region of influence of growing cracks (known as the Hui-Riedel (or HR) field (Hui and Riedel, 1981; Hui, 1983) can in fact be significant in comparison to the HRR fields. Under these circumstances the use of C(t) as a crack tip parameter is invalid. Other approaches must be considered.

C_t - Parameter

The C_t parameter (Saxena, 1986) is an extension of the stress-power dissipation rate interpretation of C^* into the transient regime. It also

Deformation Law	Expressions for Estimating the Amplitude of the HRR Field, C(t)		Reference
1. Power-law creep	C^*	---A	Landes and Begley (1975)
$\dot{\varepsilon} = A\sigma^n$			Goldman and Hutchinson (1975)
2. Elastic + power-law creep			
$\dot{\varepsilon}=\dot{\sigma}/E+A\sigma^n$			Riedel and Rice (1980)
a. SSC condition	$\frac{(1-\upsilon^2)\,K^2}{(n+1)Et}$	---B	Ohji, Ogura and Kubo (1978)
b. Transition creep condition	A + B		Ehlers and Riedel (1981)
3. Primary creep			
$\dot{\varepsilon}=A_1[\varepsilon(t)]^{-p}\sigma^{n_1(1+p)}$	$\frac{C_h^*}{A_1(1+p)t^{1/(1+p)}}$	---C	Riedel (1981)
4. Elastic + primary creep			
$\dot{\varepsilon}=\dot{\sigma}/E+A_1[\varepsilon(t)]^{-p}\sigma^{n_1(1+p)}$			
a. SSC condition	$[\frac{K^2(1-\upsilon^2)}{Et}]^{1+p}\ \frac{1}{1+n_1}$	---D	Riedel (1981)
b. Transition creep	C + D		Riedel and Detampel (1987)
5. Elastic + primary + secondary creep			
$\dot{\varepsilon}=\dot{\sigma}/E+A_1[\varepsilon(t)]^{-p}\sigma^{n_1(1+p)}+A\sigma^n$	A + C + D		Riedel and Detampel (1987)

A, n, p, n_1, A_1 are material constants derived from creep deformation tests at several stress levels. E = elastic modulus, t = time elapsed. C^* and C_h^* are path-independent integrals, K = stress intensity parameter.

Table 1. Summary of major crack tip stress analysis results in creeping bodies.

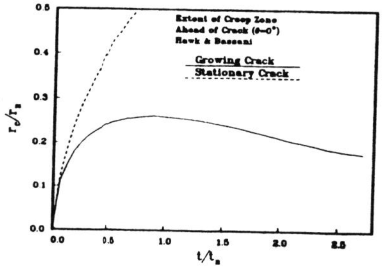

Fig. 1. Normalized creep zone size as a function of normalized time for a growing and stationary crack in Mode III, Hawk and Bassani (1986).

alleviates the two primary shortcomings of the C(t) approach as will be explained in this section. C_t is defined as the instantaneous stress-power dissipation rate as follows:

$$C_t = -\frac{1}{B}\frac{\partial U_t^*}{\partial a} \tag{3}$$

where, U_t^* represents an instantaneous value at time, t, after application of the load. The parameter is defined for a stationary crack and the implications for the growing crack will be considered later in this section. Under the conditions of extensive steady-state creep it is obvious from the respective definitions that $C_t = C^*$. Therefore, under these conditions and for extensive primary creep conditions, C_t = C(t) and hence it also characterizes the amplitude of the HRR field. Under conditions of small-scale and transition creep $C_t \neq C(t)$ as shown clearly in the numerical results (Bassani et al., 1986) and reproduced in Fig. 2.

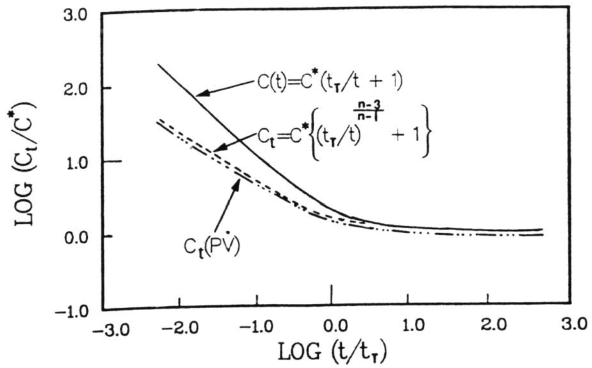

Fig. 2. Results of the stationary crack analysis of the CT Specimen, Bassani et al. (1986).

In small-scale-creep regime, a general expression for estimating C_t is derived as follows (Saxena, 1986)

$$C_t = \frac{P\dot{V}_c}{BW}\ F'/F \tag{4}$$

where, W = width of the specimen, P = applied load, F = $(K/P)BW^{1/2}$, K-calibration factor, F' = dF/d(a/W), $\dot{V}_c$ = rate of deflection at the load-line due to creep deformation. Equation (3) is equally valid for power-law or primary creep law provided small-scale-creep conditions are met. In a test specimen, if $\dot{V}_c$ is measured, the magnitude of C_t is readily obtained irrespective of the prevailing creep deformation law. In components, where $\dot{V}_c$ cannot be measured, it can be estimated under small-scale-creep conditions by (Bassani et al. 1986).

$$\dot{V}_c = \frac{2B}{E}\,\frac{K^2}{P}\,\beta \dot{r}_c\,(1-\nu)^2 \tag{5}$$

where $\dot{r}_c$ = rate of expansion of the creep zone size and β is a scaling factor and is approximately equal to 1/3 as determined from finite element analyses (Bassani et al., 1986). The value of $\dot{r}_c$ is dependent on the prevailing creep deformation law. For power-law creep and primary creep it can be obtained from the following relationship.

For power-law creep (Riedel and Rice, 1980):

$$\dot{r}_c = \frac{1}{2\pi}\left(\frac{K}{E}\right)^2\left[\frac{(n+1)AI_nE^n}{2\pi(1-\upsilon^2)}\right]^{\frac{2}{n-1}}\tilde{r}_c(\theta)\cdot t^{-\frac{n-3}{n-1}} \tag{6}$$

For primary creep (Riedel, 1981):

$$\dot{r}_c = \frac{K^2\tilde{r}_c(\theta)}{2\pi}\left[\frac{I_{n_1}E}{2\pi(1-\upsilon)}\right]^{\frac{2}{n_1-1}}\left[(n_1+1)(1+p)A_1\right]^{\frac{2}{(1+p)(n_1-1)}}$$

$$\cdot\left[\frac{1}{1+p}\right]\left[\frac{2}{n_1-1}\right]t^{\left[\frac{2}{(1+p)(n_1-1)}\right]-1} \tag{7}$$

It should be pointed out that both Egs (6) and (7) are strictly valid for stationary cracks only. However, they may be used for slowly growing cracks defined by the condition $\dot{a} \ll \dot{r}_c$. Expressions for estimating $\dot{r}_c$ which account for growing crack effects are currently not available. Hence, even though there is no fundamental difficulty in the use of C_t for situations where crack growth effects significantly influence $\dot{r}_c$, there are practical limitations due to lack of adequate analyses. However, this is not a problem in test specimens where $\dot{V}_c$ is easily obtained from the measured deflection rates following the deflection rate partitioning method (Saxena et al., 1984). By combining Eqs 6 and 5, the relationship between C_t and the crack tip creep zone size is easily derived. This relationship is unique for a fixed applied value of K. Thus, C_t can relate the load and deflection rate measurements made at the load-point which is remote from the crack tip to the crack tip creep zone expansion rate. The following equations relates C_t to C(t) under the small-scale-creep condition (Saxena, 1981).

$$(C_t)_{ssc} = \beta(1-\upsilon^2)\,\frac{n+1}{n-1}\,(F'/F)\,\frac{r_c}{W}\,(C(t))_{ssc} \tag{8}$$

Since r_c is a function of applied K and time, t, the relationship between $(C_t)_{ssc}$ and $(C(t))_{ssc}$ is not unique. Often, creep crack growth data are correlated with crack tip opening displacement (CTOD) rate, $\dot{\delta}_t$. The following relationships can be derived between C_t and C(t) and $\dot{\delta}_t$ in the small-scale-creep regime (Saxena, 1988):

$$(C_t)_{ssc} = (2\pi\beta)^{1/2}\,(F'/F)\,\left(\frac{Kr_c}{W}\right)^{1/2}\dot{\delta}_t \tag{9}$$

$$(C(t))_{ssc} = \frac{n-1}{n+1}\,\frac{1}{1-\upsilon^2}\left(\frac{2\pi}{\beta}\right)^{1/2}\frac{K}{r_c^{1/2}}\,\dot{\delta}_t \tag{10}$$

Neither of the two parameters are uniquely related to $\dot{\delta}_t$ in the small-scale-creep region. In the extensive creep region, $\dot{\delta}_t$ and C^* are uniquely related.

Over a wide range of creep deformation conditions ranging from small-scale to extensive creep, it was shown in the above discussion that neither parameters, C(t), C_t or $\dot{\delta}_t$ are uniquely related to each other. However, in the extensive creep region the relationship is infact unique. In correlating wide range creep deformation data a good correlation with one of these parameters necessarily implies no unique correlation with the others. Figures 3 and 4 show the creep crack growth data correlations with C_t and C(t). From these results it is concluded that C_t parameter is most appropriate for correlating wide range creep crack growth data.

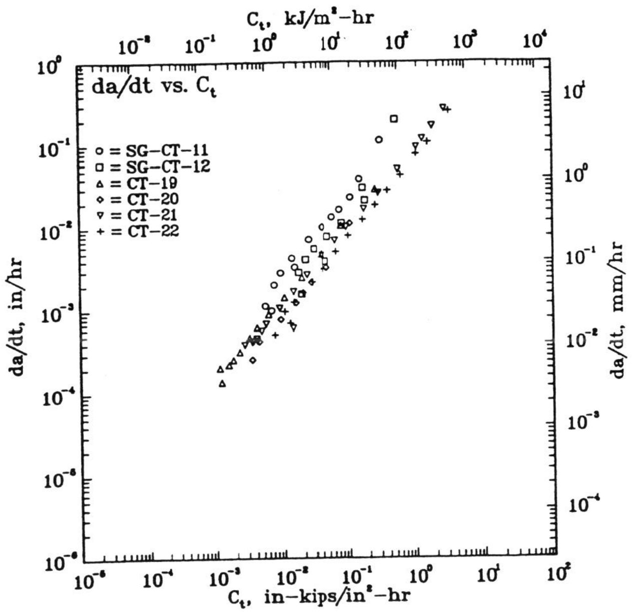

Fig. 3. Creep crack growth rate as a function of C_t in a Cr-Mo-V steel at 594°C.

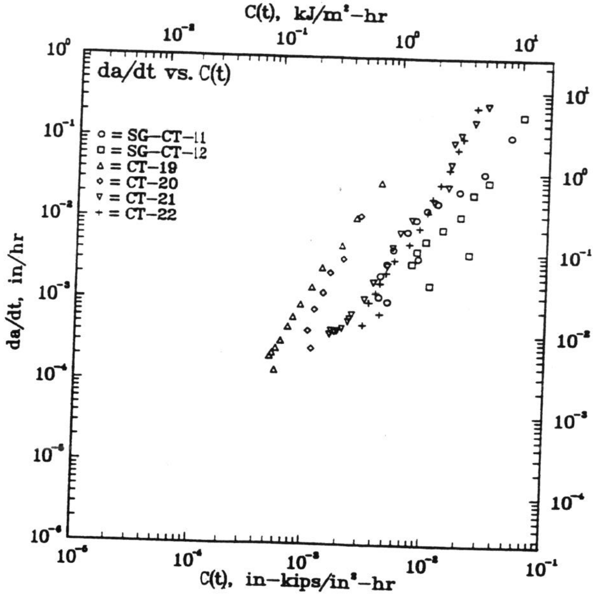

Fig. 4. Creep Crack growth rate as a function of the C(t) in a CrMoV steel at 594°C.

APPLICATION OF TDFM IN LIFE PREDICTION

As mentioned earlier in this paper, there are several potential applications of TDFM concepts in life prediction analyses of elevated temperature components. In this section a methodology for predicting creep crack growth life is described. Subsequently, the methods for predicting creep-fatigue crack growth life are also briefly discussed. Some areas which need further development to achieve greater accuracy in life prediction are outlined at the end of this section.

Prediction of Creep Crack Growth Life

Figure 5 shows a general methodology for predicting the remaining creep crack growth life of an elevated temperature component (Saxena and Liaw, 1985). The top of the figure shows the type of specimens used in material testing, and the data obtained from these tests. Material data needed are fracture toughness (to establish the crack size which will cause rupture), creep deformation properties, the tensile stress-strain properties and the creep crack growth rate behavior. Crack growth rates in structural components are predicted using the calculated value of C_t. These rates are integrated to develop the crack size versus time curve or the remaining life

versus crack size curve. The procedure outlined above is similar to the procedure used for predicting fatigue crack growth life except, fatigue cycles are replaced with time and ΔK (cyclic stress intensity parameter) is replaced by C_t.

Most components such as steam pipes or gas turbine disks are periodically shut down. This has a very significant influence on the estimated value of C_t. As time elapses the relative contribution of the transient term in estimating C_t decreases as steady-state conditions dominated by C^* are approached. When load interruptions occur, the stress relaxation process is also interrupted. Upon re-start the stress relaxation process is reinitiated independent of the relaxation in the previous cycle if small-scale-creep conditions dominate. This is schematically illustrated in Fig. 6 where a step increase in C_t value is shown following each start-up.

Since the methods of TDFM are complex and the remaining life is affected by so many factors, it is desirable to conduct the analyses with the help of a computer. Several personal computer based (Saxena, 1987; Wells, 1986) computer programs are now available for predicting creep crack growth life in specialized components. Figure 7 shows results from example calculations of creep crack growth life of a high temperature steam pipe (solid lines) containing surface defects in the radial-axial plane for several operating pressures. The dotted lines show the coresponding maximum allowable half crack lengths for assuring a leak-before-break situation. These calculations were performed using the PCPIPE computer code.

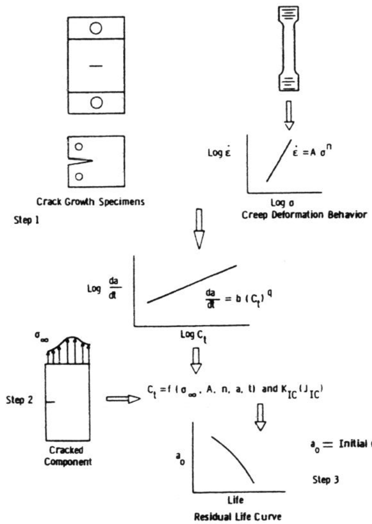

Fig. 5. Methodology for predicting crack propagation life using time-dependent fracture mechanics (TDPM) concepts.

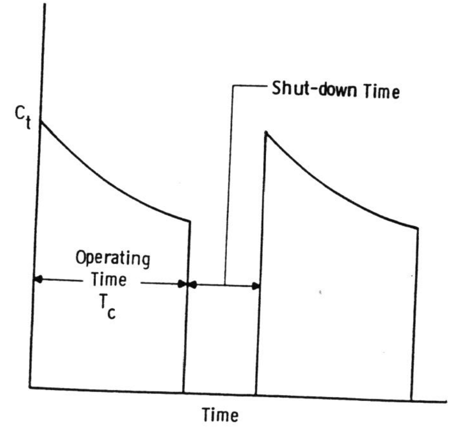

Fig. 6. C_t as a function of time operation.

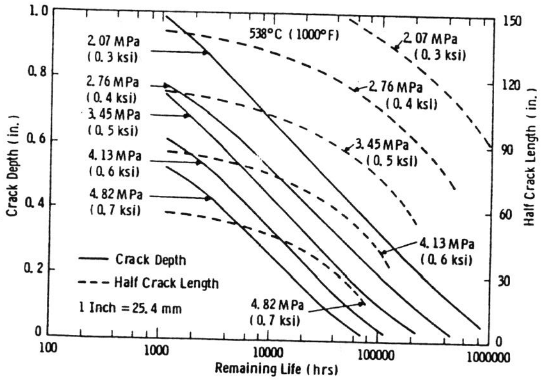

Fig. 7. Influence of steam pressure remaining crack growth life of steam pipes containing surface defects and operating at 538°C.

Crack Growth Due to Creep-Fatigue

The approach which has been most widely used to characterize creep-fatigue crack growth is to sum the cycle-dependent ($(da/dN)_0$) and time-dependent contributions to crack growth to obtain an overall crack growth rate (da/dN) for the cycle (Saxena et al., 1981). The governing equation for such an approach is:

$$\frac{da}{dN} = (da/dN)_0 + \int_0^{t_c} (da/dt)dt \qquad (11)$$

where, t_c = cycle time and da/dt is the average time dependent crack growth rate. Within this general approach there are some variations between researchers. Nikbin and Webster (1988) estimate da/dt from creep crack growth tests to calculate the time-dependent contribution. This implies that there is no creep-fatigue interaction which influences the time-

dependent crack growth behavior. Our approach (Saxena and Gieseke, 1987) obtains da/dt from creep-fatigue tests which implies that creep-fatigue interactions cannot be ruled out as a general rule. For materials which do not show creep-fatigue interactions, both approaches are identical.

There are also apparent variations in the crack driving force used to characterize da/dt among the two approaches. Webster and co-workers use C^* to characterize da/dt in a cyclic situation where small-scale-creep is expected to dominate during one cycle. Our approach uses the $(C_t)_{avg}$ parameter which is the average value of C_t during the cycle to characterize da/dt. Figure 8 shows the correlation between da/dt and $(C_t)_{avg}$ in a 1Cr-1MO-0.25V steel (Banerji and Saxena, 1988) at 427°C and 538°C for a trapezoidal loading waveform with hold times ranging from a few seconds to twenty-four hours. A single plot is obtained for different hold times and also for different temperature. Such collapsing of data into a single trend for widely varying conditions is valuable for life prediction schemes.

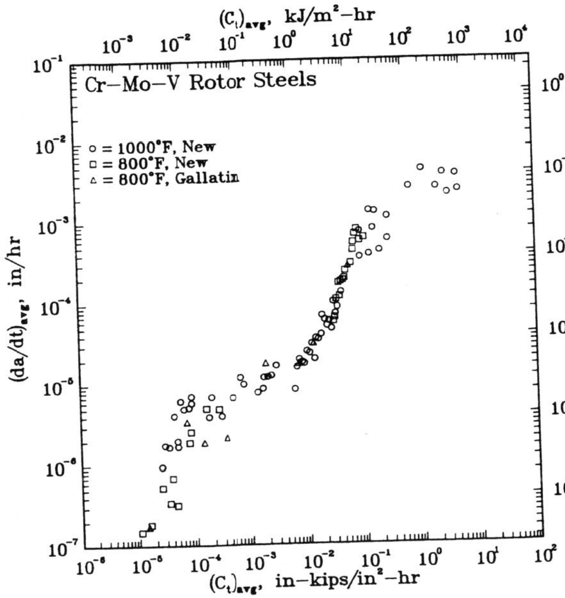

Fig. 8. Creep-fatigue crack growth rate data in Cr-Mo-V steel for trapezoidal waveforms with hold times ranging from 50 seconds to 24 hours and at temperatures of 427°C (800°F) and 538°C (1000°F).

Other approaches used for characterizing creep-fatigue crack growth (Ohji and Kubo, 1988) sum driving forces according to cycle and time-dependent parts. This gives rise to a combined ΔJ_c parameter which is the sum of ΔJ_f, the time-independent cyclic J-integral and the integral of C^* over the cycle period. The relationship between ΔJ_c and the crack tip stress, strain or a related quantity is not clear. For a detailed discussion of these approaches, the readers are referred to another paper (Gieseke and Saxena, 1989).

Recommendations for Future Work

Several problems of cracking in elevated temperature components result from thermal-mechanical stresses. As yet, there are no accepted approaches for predicting crack growth due to thermal-mechanical loading. Little work has been done in the area of transition from slow creep crack growth to fast fracture which may hold the key to accurate predictions of leak-before-break conditions. Additional work in the area of predicting time-dependent crack growth for long cycle times from laboratory tests conducted over short cycle periods is needed. On the analytical side, accurate methods are still needed for estimating C_t for complex material constitutive laws which properly account for effects due to primary creep, cyclic loading and crack growth. The solutions for estimating C^* are limited to only a few geometries and almost exclusively to 2-dimensional crack cases. This area also needs attention in the future.

SUMMARY AND CONCLUSIONS

This paper summarizes the recent developments in time-dependent fracture mechanics (TDFM) over the past few years. The applications of TDFM concepts have also kept pace with the new developments. The following conclusions can be drawn at this time about the status of the field.

1. It is now widely accepted that under the conditions of extensive steady-state creep, the creep crack growth rate is characterized by C^*.

2. Significant progress has occurred in the understanding of creep crack growth behavior under transient conditions to includes the effects due to small-scale-creep, primary creep and cyclic loading. C_t appears to be a promising candidate parameter for unifying the crack growth during the transient conditions with those during the steady-state conditions.

3. Applications of TDFM have kept pace with the concept developments largely because of the timely appearance of user-friendly computer codes.

4. Areas needing further development include crack growth due to thermal-fatigue, extension of the available C^* and C_t solutions and accurate models for predicting crack growth due to creep-fatigue.

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