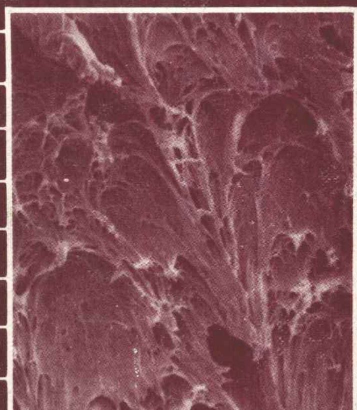
NONLINEAR FRACTURE MECHANICS

Time-Dependent Fracture



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Time-Dependent Fracture

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Foreword

This publication, *Nonlinear Fracture Mechanics: Volume I—Time-Dependent Fracture,* contains papers presented at the Third International Symposium on Nonlinear Fracture Mechanics, which was held 6–8 Oct. 1986 in Knoxville Tennessee. ASTM Committee E-24 on Fracture Testing sponsored the event. The cochairmen for the symposium section on Time-Dependent Fracture were A. Saxena, Georgia Institute of Technology, and J. L. Bassani, University of Pennsylvania. Both men, along with J. D. Landes, University of Tennessee, served as editors of this publication.

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OVERVIEW

Elastic-Plastic Fracture Mechanics (EPFM) had its birth in the late 1960s and early 1970s. In nearly two decades of growing effort, the field has seen a maturing trend as well as a change in emphasis. EPFM developed in response to a real technology need: the parent technology, linear elastic fracture mechanics (LEFM), did not apply to many of the engineering materials used in modern structures. New and better materials were developed to attain more ductility and higher fracture toughness. Where LEFM could no longer be used for analyzing failures in these materials, EPFM provided the solution. To organize and document the results of the growing research effort in the field, ASTM Committee E-24 on Fracture Testing sponsored the First International Elastic-Plastic Fracture Symposium in Atlanta, Georgia, in 1977. The bulk of this symposium, as peer-reviewed papers, is published in *ASTM STP 668, Elastic-Plastic Fracture*. Subsequently, a second international symposium on this subject was held in Philadelphia in 1981, which resulted in the two-volume *ASTM STP 803, Elastic-Plastic Fracture: Second Symposium*.

The 1980s saw a rise in more general interest in nonlinear fracture mechanics topics, particularly time-dependent fracture mechanics. Therefore, the title for the next symposium was modified to include this emerging field. As a result, the Third International Symposium on Nonlinear Fracture Mechanics was held in Knoxville, Tennessee, in 1986. This symposium, sponsored by ASTM Committee E-24 and its Subcommittee E24.08 on Elastic-Plastic and Fully Plastic Fracture Mechanics Technology, featured both time-dependent and elastic-plastic topics in fracture mechanics. The time-dependent fracture mechanics papers are published in Volume I (this volume) of this Special Technical Publication (*ASTM STP 995*). Volume II features the elastic-plastic contributions to the symposium.

In the mid-1970s, when consensus in the approaches to elastic-plastic fracture was emerging, the attention of some researchers shifted to elevated-temperature crack growth behavior. The motivation for this work came primarily from projects active at the time, and was directed toward building commercial advanced nuclear reactors, improving energy conversion efficiencies of conventional power plants and jet engines, exploring the feasibility of alternate energy sources such as coal gasification, and understanding failures in major equipment, such as Tennessee Valley Authority's Gallatin steam turbine rotor. New concepts which could adequately account for the presence of time-dependent creep strains in cracked body analysis were needed for integrity assessment and prevention of failures in these components. A creep analog to the J-integral called C^* was proposed in 1974, which over time has proven to be the first major breakthrough in the development of time-dependent fracture mechanics (TDFM). In its range of applicability, C^* is now a well-accepted crack-tip parameter.

At the time of the second elastic-plastic fracture symposium in 1981, it was becoming clear that the application of C^* is limited to cracked bodies undergoing dominantly secondary-stage creep. Researchers were engaged in understanding the limitations of C^* and also in extending the concept into the small-scale creep (SSC) regime, where a good portion of the practical problems lie. Only single session was devoted to papers on this subject at the second symposium. In the third symposium, TDFM was one of the prominent themes and several sessions were organized on the subject. The papers from these sessions are included in the first section of this volume.

Creep Crack Growth

The papers on creep crack growth deal with the issues of crack growth under small-scale creep conditions, the usefulness of the recently proposed C_t parameter, the applicability of damage mechanics concepts in understanding micromechanics and micromechanisms of creep crack growth, embrittlement due to aging in service and its influence on creep crack growth behavior, and experimental methods. While significant progress has occurred since the last symposium on this topic, a lot more remains to be done. Some issues not addressed in the papers at the symposium include the influence of cyclic loading and inclusion of creep deformation other than that represented by power-law creep. These are areas of current research. Also, further evaluation of the C_t parameter is likely to continue until a consensus can be reached, and stable and unstable crack growth and fracture at elevated temperature should be addressed. Therefore, a good number of problems still remain unresolved in this area. Although some of the original reasons for developing TDFM are no longer the primary driving force, the field has found considerable use in remaining life assessment of fossil power-plant components and will be useful in the development of advanced aircraft. Hence, this area is expected to be represented in future symposia on nonlinear fracture mechanics.

Dynamic Fracture

The second section of this volume is devoted to dynamic fracture. This is also one of the newer areas of research in fracture mechanics. The papers in this section deal with the issue of calculating the crack driving force, with proper emphasis on inertial effects and the measurement of fracture toughness under conditions of high rate loading. This area continues to be of significant interest to the nuclear power industry and the U.S. Navy.

Cyclic Loading

The papers in the section on cyclic loading are concerned with experimental evaluation of ΔJ for characterizing fatigue crack growth behavior under gross plasticity conditions and with cracking under mixed-mode loading. Crack-tip mechanics under cyclic loading was studied by measuring displacements, using optical interferometry. Damage accumulation in the form of dislocation motion at the crack-tip field was modeled in another paper.

Fracture of Nonmetals

The final section of the book is devoted to papers based on exploratory work in the area of fracture in nonmetallic materials, such as polymers and ceramics. This is an emerging field in which there is considerable need for new ideas.

On glancing over the Third International Symposium on Nonlinear Fracture Mechanics and Volume I of this Special Technical Publication, it is clear that very significant progress has occurred in the field of TDFM. The field is not very far along in its readiness for applications when we compare its recent progress to the status of its parent technologies, LEFM and EPFM. The concepts are based on sound principles which should ensure their widespread acceptance and usage in the future. The same is true for the status of dynamic fracture mechanics. In the area of cyclic loading, the ΔJ parameter has survived ten years of criticism, and it appears that the theory behind its success in correlating experimental data is becoming increasingly understood. Fracture mechanics of new materials such as polymers, ceramics, and composites are fields in which considerable interest is expected in the near future.

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Creep Crack Growth

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Evaluation of the C_t Parameter for Characterizing Creep Crack Growth Rate in the Transient Regime

REFERENCE: Bassani, J. L., Hawk, D. E., and Saxena, A., **"Evaluation of the C_t Parameter for Characterizing Creep Crack Growth Rate in the Transient Regime,"** *Nonlinear Fracture Mechanics: Volume I—Time-Dependent Fracture, ASTM STP 995,* A. Saxena, J. D. Landes, and J. L. Bassani, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 7–26.

ABSTRACT: An in-depth evaluation of the C_t parameter, which has been proposed for characterizing the creep crack growth behavior under small-scale-creep (transient) to extensive creep conditions, is conducted. The evaluation includes a thorough examination of the assumptions made in the definition of C_t, an experimental evaluation, and a finite-element analysis of a compact specimen used in an actual creep crack growth experiment.

The experimental correlations between da/dt and C_t are extremely encouraging. C_t is interpreted as the stress-power (or energy rate) release rate during crack extension. Under extensive creep conditions, C_t therefore equals C^*, which is given in terms of a path-independent integral as well as the stress-power release rate. Under small-scale creep, C_t is shown to characterize the rate of growth of the creep zone. More finite-element analyses and experiments under highly transient conditions are recommended for completing the understanding of the creep crack growth behavior in this regime.

KEY WORDS: creep, crack, transient regime, C_t parameter, Cr-Mo-V steel, fracture mechanics, nonlinear fracture mechanics

Creep crack growth is an important concern in the design of steam turbines, boilers, and steam pipes for power plants, advanced nuclear reactor components, and aircraft engine components. Most elevated temperature components in these machines are large and are designed to resist extensive (or widespread) creep deformation. However, significant localized creep deformation that is constrained by surrounding elastic material tends to occur in the vicinity of stress raisers such as preexisting or service-initiated cracks (or crack-like defects). This constrained crack-tip creep gives rise to a strong time-dependence in the crack-tip fields and, therefore, in the crack growth behavior [*1–6*]. Even though the creep deformation is small scale, it must be properly taken into account in a sound methodology for predicting creep crack growth.

On the other hand, laboratory specimens for measuring creep crack growth rates are small

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and generally undergo extensive creep during most of the test. Therefore, to simulate exactly the conditions experienced by the components in service, it will be necessary to test full-scale models for test durations equaling the service time (40 years for electrical power generation equipment). Since such a test is impractical, there is a real need for identifying a crack-tip parameter that can characterize creep crack growth behavior under a wide range of creep conditions so that, based on the data developed in the laboratory under extensive creep conditions, the behavior of the components can be predicted. Furthermore, test specimens often do not lie entirely in the extensive creep regime, and such data needs to be meaningfully represented.

Recently, a parameter C_t has been proposed for characterizing the creep crack growth behavior under wide-range creep conditions including the transient condition of small-scale creep [*1*]. Under extensive creep conditions, the C^*-integral [*2,4,7–9*] is now widely accepted as the crack-tip parameter for characterizing creep crack growth, and it can be shown that C_t reduces to C^* in this regime.

In this paper, we will concentrate on the methodology for characterizing creep crack growth in the small-scale-creep regime and in the transition regime between small-scale and extensive creep conditions. We first carefully examine the assumptions made in the definition of C_t in an effort to understand better its mechanics basis and also its limitations. In the small-scale-creep regime it is shown that C_t is proportional to the rate of growth of the crack-tip creep zone, which is not uniquely related to an instantaneous measure of the intensity of the crack-tip stress or strain fields. Subsequently, we present some experimental results showing the correlations between creep crack growth rate and C_t. We also present detailed finite-element analyses results for both stationary and growing cracks in a compact specimen. At present, the methodology based upon C_t has been developed only for power-law secondary creep.

In the next section, the crack-tip fields for a stationary crack in an elastic, power-law creeping material are reviewed.

Crack-Tip Stress Fields

For brevity we will consider only sharp, Mode I cracks in solids that deform both elastically and by power-law (secondary) creep. Results analogous to those summarized in this section for stationary cracks that include the effects of primary creep (strain hardening) and recovery have been given by Riedel [*10*]. This investigation was based upon extensions of the power-law constitutive relations.

Total strains are taken as the sum of the elastic and creep strains: $\epsilon = \epsilon^e + \epsilon^c$. For isotropic linear elasticity, the strains are given in the usual form in terms of the stresses, Young's modulus, E, and Poisson's ratio, ν. The isotropic, incompressible power-law creep relation is given in terms of the constant material parameters $\dot{\epsilon}_0$, σ_0, and n as

$$\dot{\epsilon}_{ij}^c = \dot{\epsilon}_0 \left(\frac{\bar{\sigma}}{\sigma_0}\right)^n \frac{s_{ij}}{\bar{\sigma}} \tag{1}$$

where $s_{ij} = \sigma_{ij} - \delta_{ij}(\sigma_{kk}/3)$ is the stress deviator and $\bar{\sigma} = [(3s_{ij}s_{ij})/2]^{1/2}$ is the Mises effective stress. With $\dot{\bar{\epsilon}} = [(2\dot{\epsilon}_{ij}\dot{\epsilon}_{ij})/3]^{1/2}$, Eq 1 implies that $\dot{\bar{\epsilon}} = \dot{\epsilon}_0(\sigma/\sigma_0)^n$. In the power-law form $\dot{\epsilon}_0$ and σ_0 are not parameters to be chosen independently; often $A \equiv \dot{\epsilon}_0/\sigma_0{}^n$ is specified instead. With $\dot{\epsilon}_0$ and σ_0 kept separate, dimensional consistency is more easily seen in the results that follow.

As depicted in Fig. 1, the crack is assumed to be two-dimensional, lying in the $x_2 = 0$ plane with r and θ denoting the crack-tip polar coordinates, and $\theta = 0$ ahead of the crack

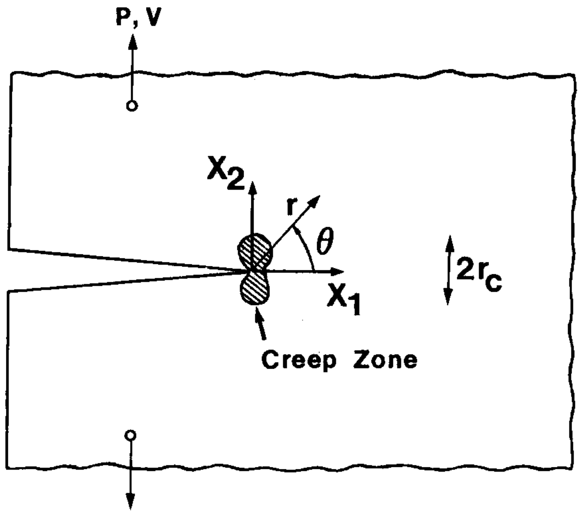

FIG. 1—*Mode I crack.*

along the $x_2 = 0$ plane. Mode I or tensile loading conditions are emphasized in the discussion below.

Stationary Cracks

The plane-strain Mode I crack under constant applied load has been investigated by Riedel and Rice [*2*], Bassani and McClintock [*4*], and Ehlers and Riedel [*11*]. Ohji, Ogura, and Kubo [*3*] have considered cracks under load variations of the form $P(t) = P_0 t^{\gamma}$, where t denotes time, and P_0 and γ are constants. Recently, Riedel [*12*] has also considered cyclic loading.

For instantaneously applied loads (or sudden load changes), the material responds elastically, since creep deformation takes time, and the crack-tip stress field ($r \rightarrow 0$) is the well-known elastic one [*2,4*]

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta) \tag{2}$$

where K_I, the elastic stress-intensity factor, and f_{ij} are known nondimensional functions of θ. For most metals undergoing power-law creep $n > 3$ in Eq 1, and this nonlinear stress dependence causes the creep strain rates to dominate the elastic ones after any sudden load changes in the high-stress crack-tip region. The form of the crack-tip stresses then resembles the Hutchinson, Rice, and Rosengren (HRR) fields in elastic-plastic fracture mechanics [*11–15*], in terms of known nondimensional functions $\tilde{\sigma}_{ij}(\theta;n)$, which are normalized with the maximum over θ of $(3/2)\tilde{\sigma}_{ij}\tilde{\sigma}_{ij} = 1$, and I_n, which is in the range 3.8 to 6.3 for plane strain, as $r \rightarrow 0$ [*2,4,16*]

$$\frac{\sigma_{ij}}{\sigma_0} = \left[\frac{C(t)}{\sigma_0 \dot{\epsilon}_0 I_n r}\right]^{1/n+1} \tilde{\sigma}_{ij}(\theta;\, n) \tag{3}$$

The amplitude factor $C(t)$ depends on the magnitude and history of the applied load, specimen geometry, crack length, material properties, and time. The size of the region around the crack tip where this field dominates is discussed below.

If a suddenly applied load is thereafter held constant, then the crack-tip stresses relax as creep strains build up around the crack tip. As long as small-scale creep (SSC) conditions persist (that is, the region where creep strains are greater than elastic strains is very small compared to crack length), the amplitude factor is approximately

$$C(t) = \frac{(1 - \nu^2)K_I^2}{(N + 1)Et} \tag{4}$$

This defines the short-time behavior. For long times under constant applied load when extensive creep occurs everywhere in the specimen, C approaches the constant, steady-state value C^*. This steady-state value is given in terms of a path-independent integral [7]. The transition time t_T between small-scale creep and extensive creep is approximated by setting Eq 4 equal to C^* [*2,4*]

$$t_T = \frac{(1 - \nu^2)K_I^2}{(n + 1)EC^*} \tag{5}$$

The values of K_I and C^* for various creep exponent n and crack sizes are tabulated for several specimen geometries and loadings in Refs *17* and *18*, respectively. Riedel [*11*] has suggested an interpolation formula for $C(t)$ between SSC and extensive creep

$$C(t) \cong C^*\left(\frac{t_T}{t} + 1\right) \tag{6}$$

In SSC the creep zone is defined as the region around the crack tip where the creep strains exceed the elastic strains [2]. A measure of the creep zone size is denoted r_c, as depicted in Fig. 1. The creep zone tends to grow in time, and its radial extent around the crack tip as a function of K_I, t, and θ is

$$r_c(\theta,t) = \frac{1}{2\pi}\left(\frac{K_I}{E}\right)^2\left[\frac{(n + 1)\dot{\epsilon}_0 I_n t}{2\pi(1 - \nu^2)\left(\dfrac{\sigma_0}{E}\right)^n}\right]^{2/(n-1)} \tilde{r}_c(\theta) \tag{7}$$

where $\tilde{r}_c$ is a nondimensional function that can be approximated in terms of the $f_{ij}(\theta)$ and $\tilde{\sigma}_{ij}(\theta;n)$ functions in Eqs 2 and 3, as plotted in Ref *2*. Otherwise, $r_c(\theta,t)$ must be determined numerically. In what follows, for plane-strain conditions, since r_c is roughly maximum at $\theta = 90°$, we will refer to $r_c(t)$ as $r_c(\theta = 90°,t)$. At $\theta = 90°$, $\tilde{r}_c(\theta) = 0.2$ to 0.5 depending on n; from our finite-element calculation for $n = 10$, $\tilde{r}_c(\theta) = 0.4$.

Fracture Parameters Associated with Crack-Tip Stress Fields

Under predominately elastic conditions—that is, when the size of the creep zone is smaller than the fracture process zone—the stress-intensity factor K_I can be used to correlate crack growth. This correlation, which is consistent with Eq 2, has been observed in laboratory tests on nickel-base alloys that are susceptible to oxidation [*19*].

At the other extreme, in behavior under extensive creep conditions ($t \gg t_T$), a large body of experimental data (see, for example, Refs *1*, *5*, *7*, *8*, and *9*) supports a correlation between