MECHANICAL ENGINEERING SERIES

Dominique P. Miannay

Time-Dependent Fracture Mechanics

Springer

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With 252 Figures

Springer

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Library of Congress Cataloging-in-Publication Data
Miannay, Dominique P.
Time-dependent fracture mechanics / Dominique P. Miannay
p. cm.— (Mechanical engineering series)
Includes bibliographical references and index.
ISBN 0-387-95212-8 (alk. paper)
1. Fracture mechanics. I. Title. II. Mechanical engineering series (Berlin, Germany)
TA409 .M525 2001
620.1′126—dc21 20001018393

Printed on acid-free paper.

Production managed by Steven Pisano; manufacturing supervised by Joe Quatela.
Camera-ready pages prepared from the author's Microsoft Word files.
Printed and bound by Sheridan Books, Inc., Ann Arbor, MI.
Printed in the United States of America.

9 8 7 6 5 4 3 2 1

ISBN 0-387-95212-8 SPIN 10791580

Springer-Verlag New York Berlin Heidelberg
A member of BertelsmannSpringer Science+Business Media GmbH

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(continued after index)

To my family

Mechanical Engineering Series

Frederick F. Ling
Series Editor

Series Preface

Mechanical engineering, an engineering discipline borne of the needs of the industrial revolution, is once again asked to do its substantial share in the call for industrial renewal. The general call is urgent as we face profound issues of productivity and competitiveness that require engineering solutions, among others. The Mechanical Engineering Series features graduate texts and research monographs intended to address the need for information in contemporary areas of mechanical engineering.

The series is conceived as a comprehensive one that covers a broad range of concentrations important to mechanical engineering graduate education and research, We are fortunate to have a distinguished roster of consulting editors on the advisory board, each an expert in one of the areas of concentration. The names of the consulting editors are listed on the facing page of this volume. The areas of concentration are: applied mechanics; biomechanics; computational mechanics; dynamic systems and control; energetics; mechanics of materials; processing; thermal science; and tribology.

Austin, Texas

Frederick F. Ling

Preface

This book is the natural continuation of the book entitled *Fracture Mechanics*, published first in French in 1995 by Les Editions de Physique, and then in English in a revised, updated, and expanded form in 1997 by Springer-Verlag, New York.

The first book reviewed the failure of cracked bodies under static loading and with possible quasi-static or stable crack propagation in isotropic and homogeneous continua. The present work is divided into three main parts. This continuation begins with a general treatment of the practical use of fracture mechanics in terms of relevant material properties and loading. Then the basic knowledge of dynamic-fracture mechanics and of creep-fracture mechanics in isotropic and homogeneous continua is successively presented. The other important issue in fracture mechanics, fatigue-fracture mechanics, is excluded, but some elements can be found here. It is assumed that readers will be familiar with the matter contained in the first book and acquainted with the elementary definitions.

The book aims to be a reference book for postgraduate students, scientists and engineers working in the field of materials, structural design, non-destructive evaluation and safety assessment. The book is more particularly devoted to metallic materials.

The first two chapters feature details of the most up-to-date review of the development of fracture analysis, and of the practical uses of fracture mechanics. Basic ideas, as well as current estimation approaches, for the structural analysis of industrial components are given. These chapters can also be considered a practical illustration of volume 1, and of parts on dynamic- and creep-fracture mechanics of this volume.

In the first chapter, emphasis is placed on the ductile-to-brittle transition of steels. In chronological order, after measuring toughness by the ductility from the tension test of smooth specimens, the noxiousness of notch and loading was recognized and Charpy testing was developed to screen metals with consideration of fracture initiation. With the appearance of large monolithic structures such as the ship hull, fully dynamic aspects of crack propagation and arrest were treated by Pellini and colleagues. Subsequently, thick structures such as nuclear pressure vessels appeared and the effect of thickness was taken into account by Wessel and colleagues at Westinghouse, and then codified by the American

Society of Mechanical Engineers. However, the need to infer toughness characteristics of materials, and not from geometry from small specimens, particularly when the available amount of metal is small, was always present and the master-curve concept for the transition toughness is proposed. Other methods, such as the small-punch test, the indentation test, and the miniaturized-specimen tests, are developed to study flow properties, fracture-impact energy and toughness transition. The end of the chapter is an extension of the first volume and is devoted to the constraint effect, and to the warm-pre-stressing effect.

The second chapter is devoted to the historical development of engineering methods, also called simplified methods, for assessing the risk of fracture of components under design or in service, and giving a sufficient basis for the comprehension of the procedures. Different methods under development in different countries are described, and more particularly the English R6 rules in the case of brittle and ductile fracture at relatively low temperatures, and the English R5 and R6 rules and the French Appendix A16 procedure of the RCCM-MR code in the case of creep fracture at high temperature. The French work on simplified methods in the case of thermal shocks is also given and analyzed. The classification into primary and secondary stresses is explained, and the calculus of safety margins based on probabilistic and deterministic models for measuring the reliability of structures is given. These bases allow for the comprehension of the French RSEM code.

The next three chapters describe the dynamic aspect of fracture mechanics.

The third chapter presents an approach to high-loading-rate characteristics with inertia effect and an elementary background on the knowledge of the constitutive-flow rules under dynamic conditions in terms of stress, strain hardening, strain rate and temperature. Thermally activated and phonon viscous-drag controlled deformation rates are introduced. The more usual elastic and visco-plastic laws are described and the experimental procedures to identify them are given. Next, the micromechanisms of dynamic fracture by cleavage, identical to that of static loading but with different criteria, ductile tearing identical to that of static loading but with different criteria, and adiabatic shear specific to dynamic loading are reviewed, the experimental investigation procedures are described. Finally, equations of continuum-damage mechanics for ductile rupture are given.

The fourth chapter presents the behavior of a stationary crack in an elastic continuum under stress-wave loading. This behavior is given by an analytical time-dependent stress-intensity factor that describes the stress-and-strain singularity fields around the crack tip with a spatial distribution identical to that of a crack under static loading. Optical experimental methods to measure the stress-intensity factor are described. After describing the testing procedures allowing a very high loading rate, the main types of variation of dynamic brittle- or ductile-initiation and stable-propagation toughness of polymers and metals with loading rate are provided, and their links to fracture criteria, such as they are now more or less empirically understood, are given. Some insight is gained by analyzing the build-up of the visco-plastic zone in the small-scale yielding regime.

In chapter five, the dynamic propagation of a crack in an elastic medium subjected to loading is studied. The elastic singularity field is described by a stress-intensity factor depending on the crack velocity, and by spatial functions depending also on velocity. To adequately describe the strong transient propagation, the higher-order terms of the asymptotic development are to be considered. The energy concept is presented either under its analytical form as a J-contour integral, or as an energy balance to define a crack driving force. No direct equivalence between stress-intensity factor and crack driving force exists, and these two quantities are used to describe the dynamic crack resistance. Crack arrest toughness is defined and the experimental procedures to determine it are given. When the visco-plastic response of the material is taken into account under the small-scale yielding-regime hypothesis, a description of visco-plastic zone is available and dynamic-crack resistance is explained with the help of microscopic fracture criteria identical to those of the static case, or by continuum-damage mechanics for ductile tearing. However, understanding is made difficult by the actual heterogeneous and nonsimilar nature of propagation.

The theory for analyzing creep-crack initiation and propagation is the topic of the last two chapters.

The sixth chapter presents, firstly, an elementary background on the knowledge of constitutive-flow rules under creep conditions in terms of stress, strain rate and temperature. The dislocation, and the point-defect motions responsible for the deformation, are described. The deformation-mechanism maps with lines of equal strain rate are defined. The more customary elastic and visco-plastic laws are described. The concepts of skeletal point and reference stress are introduced. Thereafter, the micromechanisms of creep fracture are reviewed. Damage develops by void initiation and diffusion growth enhanced or hindered by dislocation creep constraints. The results are conveniently displayed as void-growth maps. The map is constructed with lines of equal damage. Final rupture occurs by void coalescence or facet microcrack coalescence. Phenomenological and micromechanism continuum-damage mechanics are given.

In chapter seven, the creep initiation and propagation of a crack in a creeping elasto-plastic medium is studied. The time-dependent singularity fields of the stationary crack in an elasto-plastic material, creeping according to the three fundamental usual laws first studied by Riedel and Rice, are described by specific load parameters, such as the elastic-stress intensity factor, the plastic J-contour integral and the creep-contour integrals $C(t)$, C^*, C^*_h, and so forth, depending on the external loading level, and on temporal and spatial distribution similar to that of a purely plastic material. This leads to the drawing of load-parameter maps with lines of transient time. For a growing crack, the stress-singularity field is described for steady propagation according to the Hui and Riedel model by means of an amplitude factor uniquely determined by the crack velocity, and thus independent of the applied load. For K-controlled growth, the singularity field is composed by this field, by the Riedel and Rice field, and by the singular-elastic field with domain sizes depending on time and load. For the extensive creeping regime, the singularity field is described by the Riedel and Rice model. The C_t parameter, proposed by Saxena and an extension of the stress-power dissipation-rate interpretation of C^* into the transient regime, is introduced. The crack-growth data are discussed according to the these singular-loading parameters.

The morphology of crack initiation and growth, and incubation times, are discussed in terms of micromechanism and local damage according to the brittleness or the ductility of the material. Growth is analyzed according to a local approach with a stress-and-strain rate field for a damage-free material or a damaged obeying the model of Hutchinson on one hand, and with a fracture-strain criterion on the other hand. Such a treatment explains the transient regimes. Continuum-damage mechanics are also used to explain crack branching. Thus, the practical use of the different load parameters and their limitation is outlined.

In chapter eight, fatigue in the whole temperature range, and its interaction with creep at high temperature, are reviewed. Damage as it occurs in smooth specimens and structure is presented. Micromechanisms are described and the damage laws in terms of stress, strain and energy are given. Modifications commonly used when creep occurs are discussed. For fatigue-crack growth, the stress-ratio effect, the closure phenomenon for explaining the threshold, and overload, leading to retardation are presented according to their phenomenological aspect, and the local approach in terms of damage at the crack tip. When creep occurs at high temperature, the role of frequency with a transition value and hold time under constant load are presented. Limitation of the summation rule is emphasized, and the history effect linked to the loading phase and the transient nature of creep as it is currently envisaged is given.

There are exercises at the end of each chapter. Some of these include extensions of the text material. Answers to approximately one-half of the exercises are given at the end of the book.

This book results from a course taught at the Institut Supérieur des Matériaux et de la Construction Mécanique. It also represents the fulfillment of thirty years of experience in the field of fracture mechanics at the Commissariat à l'Energie Atomique.

The author should like to thank the Institut de Protection et de Sûreté Nucléaire and the Commissariat à l'Energie Atomique for their encouragement, and for the opportunity to publish this work.

June 2001 Dominique P. Miannay

Symbols

SYMBOL	DESCRIPTION
F	Force (see also P).
H	Constraint parameter in terms of stress triaxiality ratio.
J	Rice's path integral.
J_C	Cleavage elastic-plastic fracture toughness.
J_{BB}	Bounded body solution of J.
J_E, J_e	Elastic component of J.
J_{FB}	Finite-body solution of J.
J_P	Plastic component of J.
Js	J-value estimated according to a simplified method.
$Js_{RSE\text{-}M}$	J-value estimated according to the simplified method of the RSE-M code.
Js_{R6}	J-value estimated according to the simplified method of the R6 rule.
J_{sA16}	J-value estimated according to the simplified method of the A16 appendix.
J_{SSY}	Small-scale yield solution of J.
Ko	Stress-intensity factor at crack initiation, or the value of K at the onset of rapid-fracturing ASTM E 1221.
Ko	Stress-intensity factor level corresponding to a 63.2% cumulative failure probability.
KV	Absorbed energy by a broken standard Charpy V-notch impact-test specimen.
KCV	Absorbed energy per unit ligament area by a broken standard Charpy V-notch impact-test specimen.
K-EE	Equivalent-energy fracture toughness or fracture toughness of steel determined according to the equivalent-energy methodology.
K_J	An elastic-plastic equivalent stress-intensity factor derived from the J-integral.
K_{JC}	An elastic-plastic equivalent stress-intensity factor derived from the J-integral at the point of onset of cleavage fracture, J_C.
$K_{JC(med)}$	Stress-intensity-factor level corresponding to a 50% cumulative failure probability.
Kmat	Material toughness according to the R6 method.
	Constraint-corrected material toughness according to the R6 method.
K_0	Master-curve Weibull fitting parameter, or master-curve reference-fracture toughness, corresponding to a 63.2% failure probability.

K_P	Stress-intensity factor corresponding to primary stresses.
Kr	Non-dimensional stress-intensity factor parameter according to the R6 method.
K_S	Stress-intensity factor corresponding to secondary stresses.
K_T	Sum of K_P and K_S.
KIR	Reference-fracture toughness or lower-bound initiation toughness.
$K_{x\%}$	Master-curve x% lower-bound fracture toughness.
Lr	Non-dimensional load parameter according to the R6 method.
	Ratio of applied load to yield-collapse load.
LSE	Lower shelf energy.
P_A	Load at an arrest event.
P_F	Cumulative failure probability.
P_F	Fast-brittle fracture load.
Pm	Maximum load on an instrumented impact-test record.
Pu	Unstable crack-propagation load in an instrumented impact-test record.
P_{GY}	General yield load.
P_M	Maximum load.
Q	Q-stress, amplitude of the second term of an asymptotic solution for the stress field around a crack tip in a power-law hardening material.
Q	Constraint parameter in terms of opening stress.
Q_H	Constraint parameter in terms of hydrostatic stress.
RT_{NDT}	Nil-ductility-temperature reference temperature.
s	Standard deviation.
Sr	Non-dimensional load parameter according to the R6 method.
	Ratio of the applied load to flow-strength collapse load.
T	T-stress, constant stress parallel to the crack in the linear elastic crack-tip solution.
To	Master-curve material-specific reference transition temperature corresponding to median fracture toughness of 50%.
T_{KX}	Transition temperature indexed at an X J energy level when using standard Charpy V-notch impact-test specimen.
Tt	Transition temperature corresponding to 50% shear fracture.
USE	Upper shelf energy.
β	Reliability index.
$\delta 5$	CTOD spanning the original fatigue crack tip over a gauge length of 5 mm.
γ	Partial safety factor.
ρ	Shift parameter according to the R6 method.
σ	Standard deviation.
σ_f	Plastic flow stress of a metal.
σ_0	Static yield stress.

■ Dynamic Behavior

B	$B = \dfrac{1+\alpha_s^2}{4\,\alpha_l\,\alpha_s - (1+\alpha_s^2)^2}$, a function of crack-tip speed.
D	$D = 4\,\alpha_l\,\alpha_s - (1+\alpha_s^2)^2$, a function of crack-tip speed.
c_0	Elastic longitudinal wave speed in a rod.
c_d	Elastic dilatational wave speed.
c_l	$= c_d$, elastic longitudinal wave speed.
c_p	Heat capacity.
c_R	Elastic Rayleigh surface-wave speed.
c_s	Elastic shear-wave speed.
GID	Dynamic elastic toughness.
J_{Id}	Dynamic elastic-plastic initiation toughness.
k	Thermal conductivity.
K_I^d	Dynamic stress-intensity factor for a stationary crack.
$K_I^d(v,t)$	Dynamic stress-intensity factor for a growing crack.
K_I^D	Dynamic stress-intensity factor for a growing crack.
K_a	Crack-arrest fracture toughness, or the value of the stress-intensity factor shortly after crack arrest.
K_{Ia}	Plane-strain crack-arrest toughness, or the value of the crack-arrest fracture toughness, Ka, for a crack that arrests under conditions of crack-front plane-strain.
KA	Dynamic crack-arrest fracture toughness.
K_{Id}	Dynamic initiation toughness.
K_{ID}	Dynamic elastic propagating fracture toughness, or dynamic crack propagation resistance.
m	Strain-rate sensitivity exponent.
m	Normalized crack-tip growth rate, v/c_s or v/c_R.
v	Crack growth rate or crack speed or crack velocity.
v	Particle velocity.
V	Impact velocity.
H(t)	Unit step function, or Heaviside function = 0 for $t < 0$ and = 1 for $t \geq 0$.
α_d	$= \sqrt{1 - v^2/c_d^2}$.
α_s	$= \sqrt{1 - v^2/c_s^2}$.
β	Taylor-Quinney exponent, fraction of plastic work-rate density that is converted into heat.
ρ	Density.
σ_{0d}	Dynamic yield stress.

■ Creep Behavior

$\dot{a}$	= da / dt, crack growth rate.
A	Cavity area on a grain boundary.
A, m, M, M	Constants in creep-constitutive equations.
B	Constant in power-law creep expression or secondary-creep coefficient.
B_1	Primary-creep coefficient.
B_2	Secondary-creep coefficient.
B_3	Tertiary-creep coefficient.
C	Constant in Larson-Miller parameter.
C_c	Creep compliance.
C*	Steady state or secondary-creep characterizing parameter for a power-law creep-constitutive law.
	Long-time creep-characterizing parameter for an elastic power-law secondary-creep constitutive law.
	The parameter is a line-integral or the amplitude of the stress field, stress singularity in the creep zone.
	Path-independent extensive secondary-creep integral.
C(t)	Transient creep characterizing parameter for a power-law creep-constitutive law.
	Line-integral for a material with a secondary (power) creep-constitutive law.
	Amplitude of the stress field, stress distribution.
C*(t)	Time-varying value of C*.
C(t)/scc	Small-scale creep component of C(t).
C^*_h	Primary-creep characterizing parameter.
	Primary-creep path independent integral.
C_t	Short-time creep characterizing parameter or time-dependent transient-creep fracture-mechanics parameter.
	Creep component of the power-release rate.
$C^*_{(n)}$	Value of C* for power-law creep.
C^*_{ref}	Value of C* estimated from reference stress.
C^*_{exp}	Value of C* estimated from experimental data.
d	Facet diameter.
D_{gb}	Atomic grain-boundary diffusivity.
Ds	Atomic surface diffusivity.
f	Stress-enhancement factor of creep assisted by grain-boundary sliding.
k	Boltzmann's constant, = $1.38\ 10^{-23}$ J K^{-1}.
l	Cavity half spacing.
L	$= (D_{gb}\delta_{gb}\Omega/kT)\sigma_e/\dot{\varepsilon}_e)^{1/3}$, characteristic diffusion length scale parameter.
m	Time exponent in creep law.
m	Material constant in creep-strain law.
n, n1, n2	Stress exponents in creep laws.
n	Stress exponent in Hollomon and Ramberg-Osgood laws.
P	Larson-Miller parameter.

Q	Activation energy.
Q_1	Dimensionless-constant, second-order stress term in the series expansion of the stress field for a material with a secondary (power) creep-constitutive law.
R	Gas constant, = 8.315 J mol^{-1} K^{-1}.
R	Cavity radius.
r_c	Creep process zone size.
S	Externally applied (remote) axial stress.
Sr	Mean stress to rupture.
St	Time-dependent allowable stress.
t	Time.
t_1	Small-scale primary to extensive-primary creep transition time.
t_2	Extensive-primary to extensive-secondary creep transition time.
t_f	Time to fracture.
t_H	Hold time under constant load or displacement.
ti	Initiation time.
t_N	Normalized time given by $t_N = (\sigma_N/E)/\left[\dot{\varepsilon}_0/(\sigma_N/\sigma_0)^n\right]$, which is the time required for the creep strain to equal the elastic strain under a uni-axial tensile stress σ_N.
tr	Time to rupture.
tr	Rise time to maximum load during cycling.
tru	Uni-axial creep rupture life.
trm	Multi-axial creep rupture life.
t_{red}	Redistribution time prior to steady-state creep.
t_R	Reference time for steady-state crack growth under small-scale creep conditions.
t_T	Transition time between small-scale and large-scale, or extensive, creep conditions (behavior, regimes) for a material with a secondary-creep constitutive law; transition time prior to global steady-state creep.
t_{T1}	Transition time between small-scale and large-scale, or extensive, primary-creep conditions for a material with primary and secondary-creep constitutive laws.
t_{T2}	Transition time between small-scale and large-scale secondary-creep conditions for a material with primary and secondary-creep constitutive laws.
T	Remote transverse stress.
T_m	Absolute melting temperature.
U	Creep usage factor.
V	Creep-rupture usage factor.
V	Cavity volume.
α, χ, ϕ	Constants in damage-constitutive equations.
γ_b	Grain-boundary free energy.
γ_s	Surface free energy.
δ	Grain-boundary separation.
δ_{gb}	Grain-boundary thickness.