Mechanics and Materials Center
TEXAS A&M UNIVERSITY
College Station, Texas

DYNAMIC FRACTURE AND DEFORMATION OF SOLID PROPELLANT

FINAL REPORT

R.A. SCHAPERY
J.R. WALTON

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
CONTRACT N00014-86-K-0298
WORK UNIT 4324-520

MM 5488-89-12

MAY 1989

unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT

4. PERFORMING ORGANIZATION REPORT NUMBER(S) MM 5488-89-12

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Mechanics & Materials Center, Texas A&M University

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION ONR

6c. ADDRESS *(City, State and ZIP Code)* College Station, Texas 77843

7b. ADDRESS *(City, State and ZIP Code)*

8a. NAME OF FUNDING/SPONSORING ORGANIZATION ONR

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-86-K-0298

8c. ADDRESS *(City, State and ZIP Code)* Propulsion & Energetics
Office of Naval Research/Code 1132P
800 N. Quincy Avenue
Arlington, VA 22217-5000

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
			4324-520

11. TITLE *(Include Security Classification)* Dynamic Fracture and Deformation of Solid Propellant

12. PERSONAL AUTHOR(S) R.A. Schapery and J.R. Walton

13a. TYPE OF REPORT Final

13b. TIME COVERED FROM 4/86 TO 3/89

14. DATE OF REPORT *(Yr., Mo., Day)* 1989, May, 30

15. PAGE COUNT

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)* Solid Propellants, Viscoelasticity, Fracture, Crack Growth.

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report summarizes primarily theoretical research on dynamic crack growth in linear viscoelastic media and quasi-static deformation behavior of particle-filled rubber with propagating or stationary microcracks. Results from both studies are applicable to solid propellant.

(1)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION

22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Richard L. Miller, Code 1132P

22b. TELEPHONE NUMBER *(Include Area Code)* (202) 696-4405

22c. OFFICE SYMBOL

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

unclassified

SECURITY CLASSIFICATION OF THIS PAGE

SUMMARY OF WORK ACCOMPLISHED

The research has consisted of two distinct but related areas of activity: (1) analysis of crack growth in linear viscoelastic media, under the direction of Professor Walton; and (2) development of a model for predicting the deformation and fracture behavior of particle-filled rubber with propagating or stationary microcracks, under the direction of Professor Schapery. Results from both efforts have direct application to the analysis of deformation and fracture of solid propellant.

This summary is divided into discussion of these two areas. For each, we first give a general summary and then discuss the work accomplished for each type of problem studied in each area. References in which the details may be found are identified by numbers in brackets; the reference list starts on p. 9. If the work appears in a technical report and a subsequent publication, both are identified.

(1) Analysis of Crack Growth in Linear Viscoelastic Media

Emphasis of the work on crack growth has been on high-speed phenomena. This study provided, in part, important information on what determines the speed of cracks, including the upper speed limit. The analytical method which has been developed to solve the integral equations governing the mechanical fields around cracks may be used for physically inhomogeneous as well as homogeneous media. The dynamic fracture studies have been for homogeneous materials, while quasi-static conditions have been assumed for the analysis of crack growth in inhomogeneous media. In all problems a finite crack tip zone, the "failure zone", was introduced in order to achieve realistic predictions of the work available for driving the crack growth (which is called the energy release rate (ERR)).

In an investigation of dynamic steady-state anti-plane (Mode III) shear crack propagation, the problem of two parallel, semi-infinite mode-three cracks propagating in a general, infinite linearly viscoelastic body was analyzed [1,17]. A combined analytical and numerical procedure was used to calculate the work input to the crack tips in order to determine its dependence upon crack speed, material viscoelasticity and crack interaction. Motivation for this two-crack problem came in part from the conjecture by Professor Knauss that the interaction of microcracks surrounding a macrocrack tip contributes to an explanation of the relatively slow experimentally observed crack speeds in viscoelastic material. The calculations performed in this study indicate that the combined effects of material inertia, viscoelasticity and crack interaction can significantly reduce the work available to propagate each crack tip.

In a study of dynamic steady-state opening mode (Mode I) crack propagation, work input to the crack tip, ERR, was obtained as a function of crack speed [18]. An analytical expression for the dynamic ERR was obtained for a semi-infinite crack in an infinite body for very general material models. The analytical expression is suitable for convenient numerical calculation which was performed for a standard linear solid and a power-law material. These calculations reinforce the observation made previously for a Mode III crack [12] that there is a dramatic difference, both qualitatively and quantitatively, between elastic and viscoelastic materials on the dependence of the ERR on crack speed. In particular, for elastic material, with loading on the crack faces which travels with the crack tip, the ERR is a monotone increasing function of crack speed that becomes infinite at the Rayleigh wave speed. This implies that the steady-state crack speed is the Rayleigh wave speed or possibly higher. However, for viscoelastic materials, the ERR is not a monotone function of crack speed and, in particular, the calculations suggest that the steady-state limiting crack speed would be far below the glassy Rayleigh wave speed. A detailed numerical comparison between G for dynamic-steady-state and quasi-static crack propagation was made. It was found that the quasi-static ERR, G_q, is a monotone decreasing function of crack speed that very closely matches the dynamic-steady-state ERR, G_d, for crack speeds up to about 60-70% of the equilibrium shear wave speed. After that G_d increases somewhat above G_q for an interval of crack speeds and finally drops below it again for high crack speeds. Solid propellant material data suggests that the G_d vs V curve (V being crack speed) can be approximated effectively by the G_q vs V curve cut off at roughly 2 times the equilibrium shear wave speed (which is consistent with experimental data on the limiting crack speed in solid propellant).

In another investigation of dynamic, steady-state, mode I viscoelastic crack propagation, the previous results were extended for material with non-constant Poisson's ratio. An expression for the ERR was derived which is considerably more complicated for non-constant Poisson's ratio than for the constant Poisson's ratio case. Again a detailed numerical comparison between the quasi-static and dynamic G vs V curves was carried out where G is the work input to the failure zone (energy release rate) and V is crack speed.

A series of investigations of transient, dynamic anti-plane shear crack propagation were conducted. First, an analysis was undertaken of a semi-infinite mode III crack, initially at rest, that begins to propagate at a constant speed under the sudden application of tractions which subsequently travel with the crack [7,14,15]. The initial analysis produced a closed form expression for the Laplace transform of the time dependent work input to the crack tip, G(t), from which both long and short time asymptotic expansions were derived; this work input is an important quantity as it provides the energy for driving a crack.

Two significant observations to emerge from this study are that: (i) whether or not a crack-tip failure zone is incorporated into the model can greatly effect both qualitatively and quantitatively the behavior of G(t) as a function of crack speed; (ii) the rate of convergence to the steady-state limit is greatly affected by the crack speed. In particular, it was observed that except for very fast crack speeds, G(t) with a failure zone initially decreases as a function of t; without a failure zone it is monotone increasing for all t. However, the decreasing behavior of G(t) occurs over a very small time interval whose length depends upon crack speed. The analysis leading to observation (ii) is much more complicated. The rate of convergence to steady-state is affected by both crack speed and the rate of decay of the shear modulus to its equilibrium value. The most surprising finding is that for a crack propagating at the equilibrium shear wave speed, the time rate of decay to steady-state is much slower than for both slower and faster crack speeds. Such crack speeds are in the range observed for solid propellant.

The work on transient effects was then extended to the layer geometry in order to study the effect of stress wave reflections off of a material boundary on the work input to the crack tip; this study will initially appear in a forthcoming Ph.D. dissertation by John Watret. The work illuminates the complex interplay among the variables: crack speed, shear wave speed, stress relaxation time, failure zone size and layer thickness upon the work input to the failure zone. These studies of mode III, dynamic, transient growth have all assumed that the crack is driven by loads travelling with the advancing crack tip, such as in a burning crack tip in solid propellant. The analysis for a semi-infinite crack in an infinite body was generalized to allow for the driving load to be stationary relative to the advancing crack tip while the failure zone stresses travel with the crack tip. Consideration of such a model is motivated by the experimental results of Knauss on dynamic crack growth in solithane rubber. The principal focus of the analysis of this problem has been determining the loading rates that lead to stable/unstable crack growth and crack arrest based upon a critical work input to the failure zone. It was shown, for example, that sustained crack propagation at speeds above the equilibrium shear wave speed can only be maintained by applying loading rates that increase exponentially in time.

Investigations of the effect of material inhomogeneity on quasi-static crack propagation in viscoelastic material are covered in [2,9,11]. A closed form solution for the stress field was obtained for the problem of a semi-infinite Mode I crack propagating through an infinite, inhomogeneous, isotropic, linearly viscoelastic body. The material was characterized by a constant Poisson's ratio and a shear modulus with a very general time dependence and a power-law dependence on depth from the crack plane. A closed form expression for the ERR was derived which clearly exhibits the dependence upon material viscoelasticity and inhomogeneity.

(2) Deformation and Fracture Analysis of Particle-Filled Rubber

A micromechanical model of deformation behavior was developed that includes explicit effects of distributed microcracking in the matrix phase (rubber) and a high concentration of relatively rigid particles. Damaged solid propellant undergoes healing when undisturbed for long periods of time; a theory for this behavior was developed in order to have a more complete model of mechanical behavior. Finally, the problem of the growth of a macrocrack in a body with distributed damage and other sources of nonlinearity was studied.

The micromechanical model for predicting effective viscoelastic stress-strain equations and microcrack growth in particle-reinforced rubber (or other relatively soft viscoelastic matrix) is described in [10]. Geometric idealization of the microstructure followed that of the composite spheres assemblage and generalized self-consistent scheme originally used for linear elastic composites without damage. The approach combined a perturbation analysis of the matrix, which becomes more accurate as the particle volume fraction is increased, with the Rayleigh-Ritz energy method for predicting mechanical response of the composite. Results for linear elastic behavior with crack growth were first obtained, and then extensions to linear and non-linear viscoelastic behavior were discussed. It was shown that the elasticity theory may be easily extended to predict mechanical response of a viscoelastic composite, and that an approximate equation governing microcrack growth is analogous to one for an aging elastic material. Finally, a limited assessment of the theory was made through comparison with some existing theoretical effective modulus results and experimental data on a solid propellant.

In [4] the essential features of a recently developed theory for elastic composites with a changing microstructure, such as microcracking, are first reviewed. This formulation, which is based on potentials like strain energy, is then illustrated by mathematically characterizing the deformation behavior of solid propellant under axial straining and confining pressure. A micromechanical model which accounts explicitly for effects of microcracking on overall deformation behavior (based partly on that in [10]) is described next. Results from this model were combined with the potential theory to predict behavior in a constrained simple shearing experiment.

The work on crack healing is covered in [6,20]. More generally, this study was concerned with the mechanics of quasi-static crack closing and bonding of surfaces of the same or different linear viscoelastic materials. Included in [6,20] is a study of time-dependent joining of initially curved surfaces under the action of surface forces of attraction and external loading. Emphasis was on the use of continuum mechanics to develop equations for predicting crack length or contact size as a function of time for relatively general geometries; atomic and molecular processes associated with the healing or bonding process were taken into account using a crack tip idealization which is similar to that used in the Barenblatt method for fracture. Starting with a previously developed correspondence principle, an expression was derived for the rate of movement of the edge of the bonded area. The effects of material time-dependence and the stress intensity factor were shown to be quite different from those for crack growth. A comparison of intrinsic and apparent energies of fracture and bonding was made, and criteria were given for determining whether or not bonding can occur. Examples were given to illustrate use of the basic theory for predicting healing of cracks and growth of contact area of initially curved surfaces. Finally, the effect of bonding time on joint strength was estimated from the examples on contact area growth.

A method of analysis of macrocrack growth in nonlinear viscoelastic media (with or without microcracks) is described in [8,19]. The method is based on the fact that, in certain cases, it is possible to construct work potentials and J-like path-independent integrals for monolithic or composite nonlinear viscoelastic media. Some situations in which such quantities exist and are useful in the study of quasi-static initiation and continuation of crack growth are discussed in [8,19]. The so-called quasi-elastic approximation and a constitutive equation in the form of a single hereditary integral provide the basis for using J or J-like integrals as fracture characterizing and predicting parameters during initiation and the early stages of crack growth. It was also shown that in some cases with significant crack growth the instantaneous crack speed can be characterized in terms of a similar path-independent integral. Finally, the problem of characterizing and analyzing growth of large cracks in viscoelastic media with micro-damage was discussed.

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