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Quarterly Progress Report

FAILURE CRITERIA FOR VISCOELASTIC MATERIALS

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The following report summarizes results on crack propagation and fracture in viscoelastic materials obtained under Research Grant NGL-05-002-005 during the time span March 1, 1969-August 31, 1969. We report on several areas of endeavor:

I Mechanical Response of an Operational Solid Rocket Propellant

a) crack propagation
b) creep behavior

II Transient Crack Growth

a) due to mechanical changes
b) due to temperature changes

III Unbonding of Dissimilar Materials

IV Crack Instability

a) in antiplane shear
b) under change of boundary load

V Publications

We proceed now to detail results for these categories.

I. Mechanical Response of an Operational Propellant

a) In order to check to what degree the crack propagation calculations for unfilled polymers are applicable to solid propellants sheet specimens were cut from a JPL ATS-propellant. Virtually no mechanical characterization of this propellant was available when it was chosen for experimentation. Consequently no estimate could be made of the crack propagation in this propellant. It turned out that the propellant undergoes dewetting very readily and therefore relieves all high stresses at a crack tip without propagating the crack. The propellant is therefore unlike others which do indeed crack readily. Arrangements are being made to secure a propellant which has caused problems repeatedly through motor cracking. Crack growth studies on propellants will continue when that propellant has been obtained.

b) Since the presently available propellant exhibits pronounced dewetting capabilities we use the available samples for studying the dewetting characteristics under a constant load in uniaxial tension. Instrumentation was transported to the Jet Propulsion Laboratory to measure time-dependent creep under various constant stress. The resulting time-dependent strain is a non-linear function of the applied stress. We view the major portion of the strain as resulting from the continual opening of voids in the propellant and from the time-dependence of the void growth. The initial set of about 25 runs has produced fairly consistent data which is now being reduced. An integral expression for the deformation has been derived which is based on micro-crack growth and the statistical distribution of defect sizes. Their growth is governed by the crack growth law derived earlier under this Grant. We await currently the end of the data reduction to determine the distribution function of the defect sizes. Some further experiments may then be necessary. The eventual result of these calculations and experiments is the establishment of a non-linear viscoelastic stress-strain relation which takes into account the internal fracture (dewetting) of the strained propellant.

II. Transient Crack Growth

a) In order to check on the validity of the simplified crack propagation equation proposed earlier and which states that the crack propagation speed is a function only of the instantaneous stress intensity factor, we have performed experiments along with the requisite calculations. Taking into account the experimental scatter one finds agreement reasonably good. Details are given in the appended report.

b) Cooling a viscoelastic material (polymer) reduces crack propagation speed under similar mechanical loading conditions. In many practical cases crack propagation is induced by cooling and the question arises therefore whether the thermally induced crack propagation force exceeds the thermal retardation of the crack. To gain insight into that behavior we have calculated the crack propagation rate in a viscoelastic strip which is being cooled from an initial temperature T_o. Results are indicated in Figure 1. One finds that there is a maximum crack propagation rate for a given initial temperature. It is clear that in a transient temperature history the total amount of crack propagation depends on both the initial temperature and on how fast the critical temperature is passed.

III. Unbonding of Dissimilar Materials

We have stated in previous work that the process of unbonding is the same as fracture except that two materials are involved instead of one. The essential difference for calculating unbonding rates rests therefore in the stress analysis, not in the physics of the problem.

We have studied in the past the fracture of a viscoelastic continuum and arrived at the relation for the crack speed (in a strip)

$$D_{cr}\left(\frac{\alpha}{\dot{c}}\right) \epsilon_{\infty}^{2} = \text{const. } \Gamma$$

where D_{cr} is the creep compliance, Γ the rate independent surface energy. For dissimilar materials the single creep compliance must be replaced by the mechanical properties of the two joined materials.

If we look at the solution of elastic cracking at the interface of two materials one finds that for incompressible materials the elastic Griffith criterion becomes*

$$\frac{1}{2}\left(\frac{1}{E_1} + \frac{1}{E_2}\right) \sigma^2 = \text{const. } \Gamma$$

One notices immediately that for the elastic case the compliance of a single material $\left(\frac{1}{E}\right)$ is replaced by the average elastic compliance of the two materials $\frac{1}{2}\left(\frac{1}{E_1} + \frac{1}{E_2}\right)$. It would seem reasonable, therefore, to conjecture that the same is true for a viscoelastic material and the rate of unbonding would therefore be governed by the equation

*V. I. Mossakovskii; M. T. Rybka, Generalization of the Griffith-Sneddon Criterion for the Case of a Non-Homogeneous Body. PMM Vol. 28, No. 6, 1964, pp. 1061-1069.

$$\frac{1}{2}\left\{D_{cr}^{(1)}\left(\frac{\alpha^*}{\dot{c}}\right) + \left(D_{cr}^{(2)}\right)\right\} \epsilon_{\infty}^{2} = \text{const.}\,\Gamma$$

so that the average creep compliance of the two bonded materials governs the rate of unbonding. It is also clear that if both materials are very dissimilar the one which is softer governs the unbonding rate. It follows further that if the compliance response transitions are shifted with respect to each other the one with shorter relaxation times dominates the crack rate at the interface.

Our next objective is to understand the deviation of a crack at the interface into one or the other of the two materials and the response of a crack at or in a strip bonded to two elastic (different) half spaces.

IV. Crack Instability

a) It has been asserted repeatedly in the literature that a crack under anti-plane shear (cf. Figure 2) will propagate in its own plane. We have run tests for this condition on Solithane 113 and found this not to be true. Instead of propagating in its own plane the crack front forms little, circular cracks which straddle the crack front at 45^{o} (cf. Figure 3).

b) It is recognized that a crack in a plane (plate) will propagate along its axis only under special loadings. For the case when the crack elongates at an angle to its axis we have formulated the problem in terms of integral equations for the in-plane problem. Difficulties have been encountered with non-uniform convergence of the solution after expanding certain integrals in terms of the crack extension size. This problem is now being investigated further.

V. Publications

Several reports have been written and submitted for publication. All have been forwarded to the NASA Contract Administrator for University Affairs.

Wnuk, M. P.; Knauss, W. G., "Delayed Fracture in Viscoelastic-Plastic Solids". GALCIT SM 68-8.
To appear in International Journal of Solids and Structures.

Mueller, H. K.; Knauss, W. G., "Crack Propagation in a Linearly Viscoelastic Strip". GALCIT SM 68-14.
Submitted to Journal of Applied Mechanics.

Knauss, W. G., "Delayed Failure--The Griffith Problem for Linearly Viscoelastic Materials". GALCIT SM 68-15.
To appear in International Journal of Fracture Mechanics.

Mueller, H. K.; Knauss, W. G., "The Fracture Energy and Some Mechanical Properties of a Polyurethane Elastomer."
GALCIT SM 69-4.
Submitted to Proceedings of the Society of Rheology.

Mueller, H. K., "Stress Intensity Factor and Crack Opening for a Linearly Viscoelastic Strip with Slowly Propagating Central Crack".
GALCIT SM 69-5.
Submitted to the International Journal of Fracture Mechanics.

Mueller, H. K., "On the Relaxation Modulus of the Equivoluminal Composition of Solithane 113". GALCIT SM 69-7.

Yamada, Y., "Experiment on Crack Propagation in a Viscoelastic Strip". GALCIT SM 69-8. Attached.

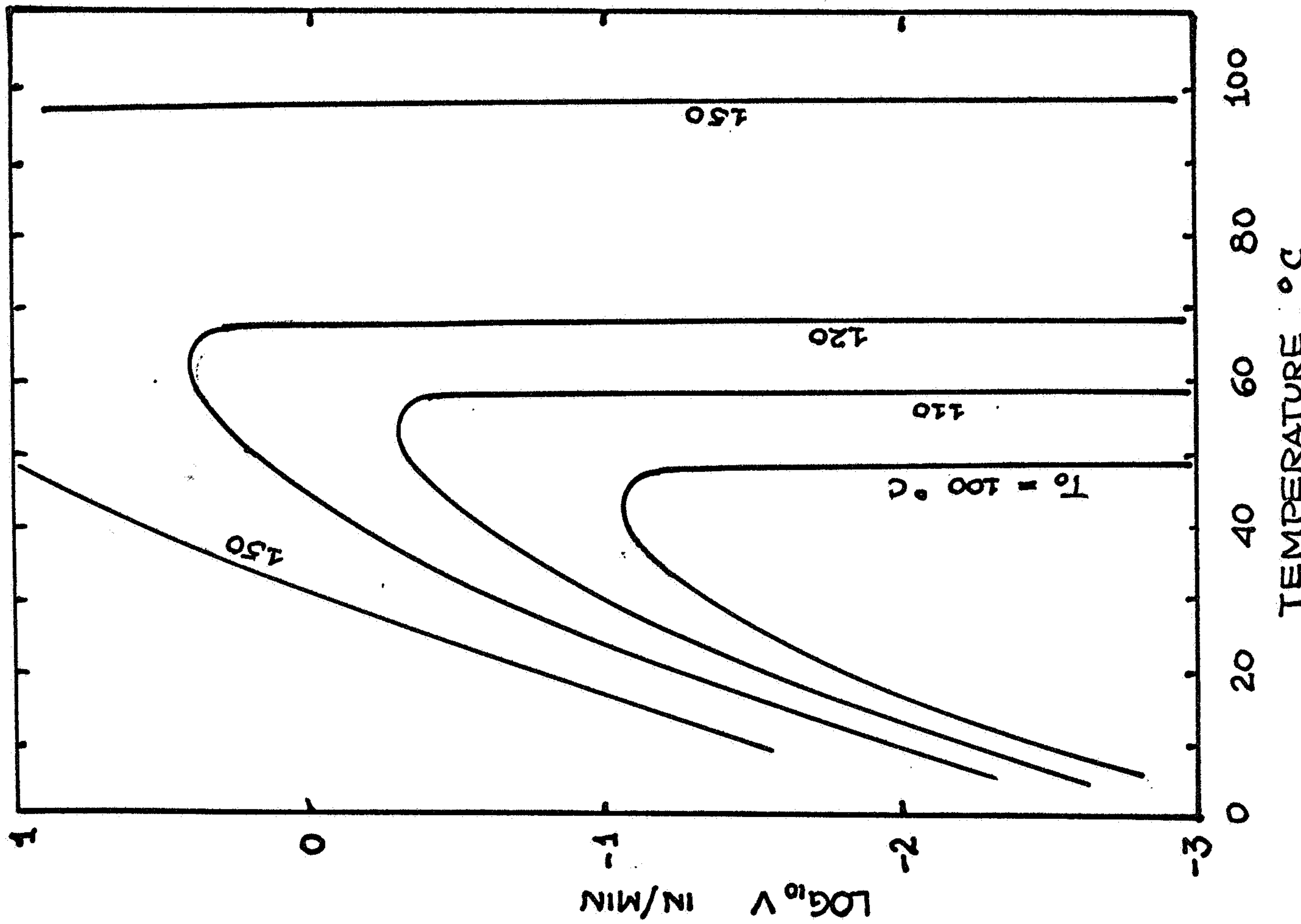
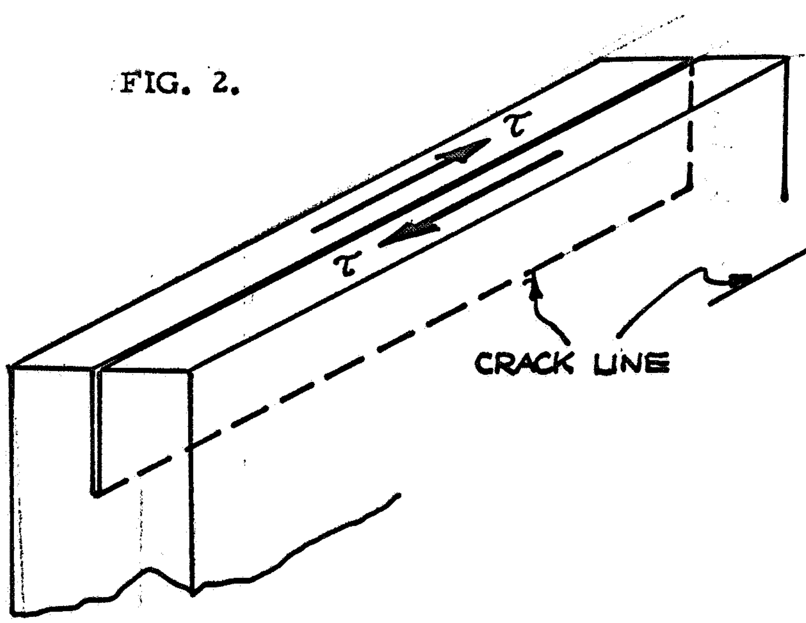


FIG. 1. CRACK VELOCITY AS A FUNCTION OF TEMPERATURE IN COOLING EXPERIMENT.

FIG. 2.



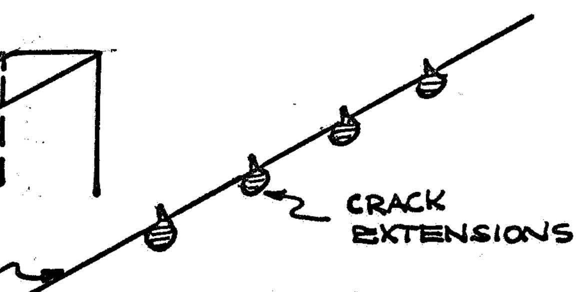


FIG. 3