The Materials and Mechanics of Rate Effects
in Brittle Fracture

Progress Report

S. J. Burns

University of Rochester

Rochester, NY 14627

716-275-4082

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Technical Progress Report

Abstract

Energy balance methods have been used to find the crack driving force in elastic fractures. The fracture toughness of cracked steel bars have been measured using these techniques. Crack tip dislocations have been shown to protect the crack tip by having a stress intensity value that is opposite in sign from the applied stress intensity value. Thus, crack tip dislocation plasticity "shields" the crack from the external stress intensity factor. In the fatigue of LiF single crystals a relationship between monotonic and fatigue hardening responses has been established using a statistical model for fatigue deformation.

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OUTLINE OF WORK IN PROGRESS DURING PERIOD

OCTOBER 1979 - OCTOBER 1980

1. Energy balance methods were used to determine the fracture toughness versus crack advance response of a material.
2. A recent report suggested to have found a generalized, non-linear fracture relationships -- it was proved that the relationships only apply to a highly restricted class of fracture specimen types.
3. Establishing a connection between crack tip dislocation plasticity and fracture by finding the stress intensity factor induced by crack tip dislocations from an elastic solution.
4. Observing crack tip dislocations using two beam electron microscopy on MgO specimens.
5. Fatigue of LiF single crystals at room and elevated temperatures -- persistent slip bands were observed and a new fatigue domain structure was found.

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Summary of Work in Progress

The crack driving force, J , is a basic concept in fracture mechanics. In linear elastic fracture, J is the strain energy release rate of the crack. In non-linear fracture mechanics it is the force that does work when the crack advances. By measuring the load versus load-point displacement on fracture specimens that differ in crack area, J values have been constructed in the load, P , versus load-point displacement, X , plot. This graphical construction only uses the measured P versus X plot so there are no assumptions as to the character of the deformation i.e. it is not restricted to the linear elastic fracture range but may be extended into the non-linear elastic range where compliance methods of fracture mechanics are not applicable.

A recent note (by Lin, Hirth and Rosenfield, Int. Journ. of Fracture, 16, R11 (1980)) reported finding a new method for recording the fracture toughness versus crack extension curve, (the R versus ΔA curve). We were able to prove that the equations used to describe this curve only apply to a highly restricted specimen type -- a fracture specimen that has both the crack driving force, J , and the load constant i.e. a non-linear constant K specimen. To our knowledge this type of fracture specimen does not exist.

Dislocation plasticity is widely recognized as being the dominant fracture toughening mechanism. For example, the high fracture toughness of metals is due to crack tip dislocation plasticity. Yet, there has been no direct connection between crack tip dislocations and fracture. An elastic stress solution has been found for a screw dislocation at the tip of a Mode III shear crack with or without external stresses. The dislocation produces a stress intensity factor on the crack in the absence of any external stresses. The value of the stress intensity factor for a dislocation, in the same plane as the crack, is $-\mu b/\sqrt{2\pi c}$, where the minus sign indicates it shields the crack tip, μ is the shear modulus, b is the Burgers' vector and c is the distance the dislocation is from the crack tip. It was also shown for many dislocations that the stress intensity factors add -- but the forces on the dislocation must include interaction with the stress free crack surface and all other dislocations. These results may be extended to edge/screw dislocations with mode I cracks. This elastic solution is a basic link between the dislocation plasticity point of view applied to fracture and the fracture mechanics discipline. The overview concept is that the crack tip dislocation arrays shield the crack tip from the applied stress intensity factor.

In transmission electron microscopy MgO specimens were observed. Dislocations

associated with cracks were seen in the samples. The cracks were on either the (100) or the (110) planes. The crack tip dislocations showed very clearly that there was a dislocation free region in front of the crack. However, these specimens were not cracked in-situ so the crack tip dislocation structures may have been modified between the cracking process and the observational time. In analyzing our micrographs we were able to identify a characteristic distance associated with the interaction between the stress free crack surface and the dislocation stress field.

The fatigue hardening response of LiF single crystals subjected to uniaxial cyclic deformation, at various strain amplitudes and strain-rates, has been related to the monotonic hardening rate. Cumulative strain in fatigue is obtained through Kocks' flow stress theory on a statistical distribution of obstacles. The difference between monotonic and cyclic deformation is in the relative rate of accumulation of short and long range internal stresses. In the case of LiF at room temperature, fatigue hardening is essentially due to the increase in short range stresses. LiF crystals which are susceptible to cleavage fracture, can withstand large tensile stresses in fatigue when compared to monotonic deformation. Activation volume analysis indicates that vacancy and jog concentrations determine the dislocation mobility and fatigue hardening of LiF single crystals. Microscopic examination reveals

the existence of very fine slip bands. In the case of crystals subjected to large number of fatigue cycles, surface irregularities and dislocation banding is observed. Optical and electron microscopy suggests dynamic recovery in the crystal studied.

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Details of Current Research

1. Crack Driving Forces

The research on this contract has established a crack driving force, J , formalized from thermodynamic concepts and applied to fracturing solids. In this contract period we have been able to calculate the J values for any specimen geometry by knowledge of the load, P , versus loadpoint displacement, X , curve for a series of test specimens that differ in crack area, A . This done as follows: A series of test specimens with selected crack areas are made. The cracks are blunted so that the specimens may be loaded without crack propagation. The P versus X curves are recorded on a single graph for all the crack areas, A_i . From report # COO-2422-13 (see Attached Reprint, Int. J. of Fracture, 16, 397 (1980)) it is known that the integrated $\oint PdX$ value between any two loading curves that differ in crack area by ΔA_i and a constant J curve is $J\Delta A_i$. J is the crack driving force value on the P vs. X plot. But the J curve is not known. However, it can be constructed as follows: Assume any J curve in the P vs. X space. This J line will cross two loading lines for different crack areas. A J value is assigned between the two loading curves by using $\frac{1}{\Delta A_i} \oint PdX = J$. Go to the next ΔA_{i+1} loading curve and

enclose an area in P-X space so that $\frac{1}{\Delta A_2} \oint P dX = J$, mark this J value on the P vs. X plot. This gives a reasonable first approximation to two constant J values in P-X space. Additional J values are constructed using this method. This second approximation to the constant J curve is now plotted on the P-X graph using the first approximated J curve. The procedure converges very quickly and a complete set of J curves are now known on the P-X plot.

A sharply cracked specimen is then tested; in this case the crack will advance and change area during the loading. The load versus load-point displacement curve is recorded and the J versus A value are read from the P-X plot. This is the J=R fracture toughness versus crack area material response for the material tested. At present we are running these tests and analyzing our data.

2. Restricted Non-Linear Fracture Relationships

The objective of fracture toughness testing is to record the fracture toughness versus crack advance curve i.e. the R versus ΔA curve. The techniques for measuring this curve are not well established. A paper by Lin, Hirth and Rosenfield (Int. J. of Fracture 16, 1980) proposed new analytic relations for recording the R versus ΔA curve. We were able to show that the proposed analysis was restricted to a very narrow class of non-linear fracture specimen

types. Specimen types that have both the load and the J value constant at the same time. A short note was written to point that the proposed analysis is highly restricted. The note is report COO-2422-25.

3. Crack Tip Shielding

Fracture in ideally brittle, flawed, elastic solids is well explained by the Griffith fracture criteria. Engineering materials have crack tip plasticity and high fracture toughness. We have been able to solve an elastic solution for dislocations near a crack tip. Thus, this solution is an analysis of crack tip dislocation plasticity. There are many solutions of crack tip continuum plasticity but the dislocation-plasticity is useful because it does not have to assume the material behavior. In the analysis we have found two new and important concepts: First, the dislocation produces a stress intensity value on the crack. This value is $-\mu b/\sqrt{2\pi c}$ where μ is the shear modulus, b is the Burgers' vector and c is the distance the dislocation is from the crack. The stress intensity values add but the forces from each dislocation do not (dislocation/dislocation interaction and interactions with the stress free crack must be considered). Second, the dislocations shield the crack tip from the external stress intensity factor. This allows a sharp crack to still satisfy Griffith's fracture criterion but maintain a high fracture toughness

value. The external (applied) fracture toughness value plus each dislocation's contribution to the fracture toughness i.e. $\sum_i \frac{\mu b}{\sqrt{2\pi}c_i}$ may be a very large number.

The crack tip shielding concept is quite easy to understand. The primary interaction between a dislocation and a crack is (rather surprisingly) the same as between a dislocation and a stress free wall. This interaction force is $\mu b^2/4\pi c$ where c is the distance from the dislocation to the wall. For the dislocation on the crack plane the force on the dislocation is the same as the force on the crack. The elastic crack force is $K^2/2\mu$, K is the stress intensity value on the crack, so, $K^2/2\mu = \mu b^2/4\pi c$ and $K = \mu b/\sqrt{2\pi c}$. K may be physically thought of as closing the crack. It is therefore opposed to an applied stress intensity value that produced the dislocation from the crack tip. The stress intensity values add because the stresses add in a problem where the boundary of the crack is maintained at constant displacement.

4. Observations of Crack Tip Dislocations

Crack tip dislocations are important in determining the fracture response of materials. For example, what is the criteria for when a crack tip blunts and the material has a ductile type fracture versus when the crack remains sharp? The nucleation of dislocations and their propagation from the crack tip determines

the fracture response of the material. By observing dislocations in transmission electron microscopy we have seen dislocation arrangements near cracks on (100) and (110) planes in MgO. The dislocations are situated near but not exactly at the crack tip. See report COO-2422-24 for the TEM micrographs. Yet closer to the crack tip the elastic stress fields would be higher and the dislocation density should be larger. In analyzing the dislocation arrangements an interaction between the dislocation and the stress free crack surface is included. This interaction suggests that there is a dislocation free region near the crack tip. The dislocation free region should be on the order of atomic dimensions. However, the observations show the dislocations to be about a 100 nm away from the crack tip. It is concluded that the dislocations nucleate at the crack tip where the atomic dimensions are important and then propagate large distances to equilibrium positions. It may also be that there are dislocation rearrangements between the nucleation time and the observational time.

5. Single Crystal Fatigue

Push pull fatigue response of LiF single crystals at room temperature is reported in Report COO-2422-23. For this material the fatigue hardening response is related to the monotonic hardening using Kocks statistical flow stress theory. In continuing this work at

a higher temperature we have observed a new fatigue structure. The observations in metals show (PSB) persistent slip boundaries and cell structures. In high temperature push-pull deformation of LiF single crystals PSB's were observed; the size scale of the PSB's in LiF were larger than the PSB's in copper crystals that are reported in the literature. Cell structures were also observed in our fatigued LiF crystals. The new structure is a "domain" pattern. The domain structures are crystallographically oriented walls of dislocations that show [100] alignments. To our knowledge these structures have not been reported in metal single crystal fatigue work. The wall structures look like magnetic bitter patterns and are low energy boundaries. Low stress amplitudes seem to favor these domain wall structures. The ease of observations in LiF crystals has been helpful in finding and observing these structures. A report is being written on the high temperature fatigue of our single crystals.

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Oral Presentations

- S.J. Burns: "Crack Driving Forces in Elastic Solids"
Fall Meeting of AIME/ASM, 1980, Pittsburgh, PA.
- S.J. Burns: "Fracture of Materials: An Overview"
Rochester Condensed Matter Symposium, June, 1980.
- B. Majumdar, "Push-Pull Fatigue of LiF Single Crystals"
Fall Meeting of AIME/ASM 1980, Pittsburgh, PA.
- B. Majumdar, "Interactions of Dislocations and Material
Inhomogeneities with Sharp Crack Tips" Fall Meeting
of AIME/ASM 1980, Pittsburgh, PA.

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Personnel Connected with Contract:

- 1) Professional Staff: S.J. Burns (22%)
- 2) Research Assistant: (Graduate Students):
B. Majumdar (100%)
J. Michener (100%)

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Technical Reports and Articles

COO-2422-23

Fatigue Hardening of LiF Single Crystals in Push-Pull
Cyclic Deformation

COO-2422-24

Crack Tip Dislocations in MgO

COO-2422-25

Discussion: "J Integral Analysis of Stable Crack Growth",
by I.-H. Lin, J. P. Hirth and A. R. Rosenfield.

COO-2422-26

An Elastic Theory of Dislocations, Dislocation Arrays
and Inclusions Near a Sharp Crack

COO-2422-27

Crack Tip Shielding - An Elastic Theory of Dislocations
and Dislocation Arrays Near a Sharp Crack

COO-2422-28

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