The Materials and Mechanics of Rate Effects
in Brittle Fracture

Progress Report

S. J. Burns

University of Rochester

Rochester, NY 14627

716-275-4082

MASTER

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October 1978 - October 1979

Prepared for the U.S. Department of Energy
under contract No. EY-76-S-02-2422

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Abstract

A thermodynamic formulation for a crack driving force has been experimentally used in linear elastic fracture mechanics, elastic plastic fracture mechanics and creep fracture. In linear elastic and elastic plastic fracture mechanics, mechanical stability criteria are established from the load versus the load point displacement in two test specimens that differ only in crack area. These tests have also been used to measure the fracture toughness in several heat treated steels. Creep cracking of PMMA has shown that there is a sharp transition to unstable fracture in a plot of the log of the steady state crack velocity versus the crack driving force at several selected temperatures. In addition, it has been shown that the athermal crack driving force is independent of rate and temperature. A new method for electronically recording the crack driving force versus the crack area has been used on double cantilevered beam specimens. Temperature and crack rate dependences have been measured near the ductile to brittle transition temperature in a low carbon steel.

Outline of Work in Progress during Period

October 1978 - October 1979

1. J_{IC} testing with mechanically unstable test specimens.
2. Fracture instability - we have been able to separate fracture instability into a mechanical instability and a materials instability.
3. Measured temperature independence of J_a during creep fracture.
4. Electronically relating the load versus the load point displacement in double cantilevered beam specimens to the crack driving force and crack area.
5. Crack velocity rate dependence near the brittle ductile transition temperature in steel.

Summary of Work in Progress

The value of the crack driving force at the beginning of crack propagation has been measured by recording the load versus the load-point displacement for at least two specimens that are identical in all aspects except that they differ in crack area. This fracture testing method is particularly useful because it may be applied to test specimens from the linear elastic region to those regions where specimens show significant plasticity. We have gained some experience in testing fracture specimens using this test method in the nearly linear elastic region and are encouraged that it may be applied to specimens that have been toughened by systematic heat treatments.

The understanding of fracture instabilities has been separated into two parts: a mechanics instability that is related to the curvature of the compliance versus crack area curve or to the curvature of the stiffness versus crack area curve; a materials instability where the crack increases its velocity and decreases the crack driving force. The materials instability even occurs when the testing specimen is mechanically stable.

The crack driving force in a double torsion test specimen may be found during creep fracture if the unrelaxed elastic shear modulus is known. Measurements of the unrelaxed shear modulus have permitted measurements of the athermal component of the crack driving force. This part of the crack driving force has experimentally been shown to be independent of both temperature and rate. Thus, it can be measured at high temperatures where the crack velocity is relatively large.

Measurements of the load and the load-point displacement in double cantilevered beam specimens have been electronically converted to voltages

Summary of Work in Progress (continued)

proportional to the crack driving force and the crack area. Thus, by appropriate instrumentation, the crack driving force versus crack area curve during crack growth may be plotted for double cantilevered beam specimens. When the crack remains on the mid-plane of the specimen, a smooth fracture curve is obtained. In the DCB specimen, however, the fracture will often not remain flat.

The crack velocity rate dependence in steel has been shown to vary rapidly during fast fracture. The slower the crack goes the larger the dynamic toughness for crack velocities that are several orders of magnitude below the wave speed. The increase in the fracture toughness with temperature near the brittle to ductile transition temperature is very large as is the decrease in toughness with increasing rate in this same temperature region. At temperatures near liquid nitrogen temperatures the dynamic fracture toughness does not change very much with either temperature nor rate.

Details of Current Research1. J_{IC} Testing

In last years progress report, article C00-2422-13 listed a new method for measuring J_{IC} . During this last year, we have continued to develop this method for measuring fracture properties in linear or non-linear fracture specimens. Several of our experimental test fixtures were redesigned to assure uniform loading on the three point bend, fracture specimens. Our test fixtures are not rigid and contribute appreciably to the overall machine compliance. These test methods do not require rigid fixtures. The compliance of the machine and the fixtures for our setup contributes significantly to unstable crack propagation. Note that we have argued that to measure J_{IC} accurately, an unstable test specimen should be intentionally chosen. We have achieved this goal by using short cracks in slightly plastic specimens in a compliant fixture. Our load-displacement curves show effects that are similar to serrated yielding in a tensile test.

Observing the discontinuous load vs. displacement curve is qualatative, experimental verification that our instability criteria are correct. However, the majority of our J_{IC} testing method has been applied to steel specimens that have been heat treated to alter their fracture behavior. These specimens fracture by either ductile void coalesence or brittle cleavage fracture. Thus, the fracture instability is achieved by both a mechanical instability and an intrinsic material instability. Separation of the causes of fracture instability during fracture is extremely difficult - for example, the mechanically unstable specimen drives the

Details of Current Research (continued)

crack faster and causes the fracture mode to change from void growth to brittle cleavage which in turn causes the test specimen to become even more unstable. Thus, these specimens are excellent for measuring J_{IC} but not particularly useful for deducing rate effects in fracture nor for studying instability.

2. Instability of Fracture

The research on this contract has established a crack driving force, J , formalized from thermodynamic concepts and applied to fracturing solids. The four papers on non-linear fracture mechanics establishes the following concepts: There is a "crack driving force" on any crack in an elastic solid; fracture instability (from slow to very rapid crack propagation) may be separated into two parts; a mechanical instability in the non-linear elastic solid surrounding the crack, this instability allows the crack to propagate by only consuming strain energy, the second instability concept is an intrinsic material instability at the crack tip where the value of the crack driving force that sustains a specified crack velocity is suddenly reduced. In this last year, significant progress has been made in predicting and understanding the instability in the non-linear elastic solid, i.e. the mechanics instability. As outlined below: For any linear elastic system, the generalized force on the crack is one-half the load on the specimen squared, times the derivative of the compliance. The stability of this crack is determined, at constant load, by the curvature of the compliance versus crack length curve. When the curvature of the compliance is positive then the crack is unstable, when the curvature is negative then the crack is stable, for a constant load. For constant displacement loading

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the stability is controlled by the curvature of the stiffness function; negative curvature of the stiffness function versus crack area is stable and positive curvature is unstable.

The mechanical stability of the general non-linear elastic specimen at constant displacement, i.e., in a very stiff fixture is determined by the sign of $\alpha = -\partial J / \partial A|_x$, where α is negative then the system is unstable. Although no general analytic expressions have been derived for α , negative α conditions may always be determined experimentally by testing two specimens that are identical in all aspects but differ in crack length. When the specimen with a longer crack length starts to fracture at a shorter displacement than the specimen with short crack length, then these specimens have negative α values and are therefore mechanically unstable. The constant load criteria instability is similar to the constant displacement instability although displacements and loads are interchanged.

Material instability in the crack tip region is not well understood and is important since it is the second half of the instability criteria. In addition, it is an intrinsic instability and is difficult to eliminate. Figure 1 shows data taken in our laboratory of slow crack propagation in PMMA on a specimen that has mechanical stability for constant displacement. The data is unique in that it is for steady state crack propagation and has been very carefully taken. (I believe this to be the best data available on slow crack propagation.) Note that it covers a very wide temperature range and an extremely wide velocity range, nearly 10 orders of magnitude in velocity. The crack driving force value is determined by independent measurements of the unrelaxed elastic constant (shear modulus)

Fig. 1. Apparent crack velocity, and corrected crack velocity versus J , corrected for thermal expansion, for slow crack propagation in PMMA. Open symbols: INSTRON data; closed symbols: dead weight apparatus data.

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as a function of temperature. This is important since the entire fracture specimen is creeping during the fracture. Now at the upper left range of this curve the crack velocity data can no longer be recorded because a very slight increase in the crack driving force causes the crack to propagate at velocities orders of magnitude faster, i.e., velocities near the wave speed. Note, that this is a material instability and it is sharp in the sense that the rate curve does not gradually bend upwards. If the rate curve were to show a negative slope, i.e. $\partial \ln v / \partial J < 0$, then the crack would be unstable from the materials point but the overall system's stability would be determined by this material instability and the mechanical stability of the specimen.

This material instability is not well understood but is a very important aspect of fracture in solids. For further details, see report C00-2422-15. It should be noted in Figure 1 that the change from stable crack propagation to unstable crack propagation is very sharp. This is an indication that there may be a change in the fracture mechanism.

3. Temperature Independence of J_a .

Figure 1 is an experimentally measured curve of the crack propagation rate versus the crack driving force for several selected temperatures.

Figure 2 shows the details of these curves at slow crack velocities. An important finding from our experimental program is that the crack velocity approaches zero, i.e. shows a sharp trend downward on the $\log v$ plot, at a specified value of J . This value is designated J_a and an important point is that J_a is independent of temperature. In figure 2, the value of J_a is shown as a dashed vertical line. The encircled points at the bottom of

Fig. 2. Apparent crack velocity, and corrected crack velocity versus J , for slow crack propagation in PMMA: details in the region of low J values. Open symbols: INSTRON data; closed symbols: dead weight apparatus data.

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Figure 2 are for cracks that had the indicated J values applied but their velocity was less than the specified log velocity coordinate. The encircled points on this figure were difficult to obtain; several points required data taking for several weeks to get just one point. The dead weight torque apparatus was designed to operate in this low velocity region still measurements here are quite tedious. However, the experimental evidence is that J_a is temperature independent (although the crack driving force must be defined very carefully) and therefore this value may be measured at high temperatures where the crack velocity is much faster and the measurements are not so tedious and time consuming. Note, this is exactly what is done in measuring the athermal component of the flow stress in a uniaxial tensile test. The flow curve is measured at very high temperatures where only the athermal component of the flow stress is present. The flow stress at some lower temperature has two parts, the athermal component and the thermal component. In the fracture case, since J is defined as a driving force, it is not necessary to correct the J_a value for the temperature dependence of the elastic constant.

The double torsion test is a specimen that has several advantages over other fracture test methods: the test specimen is a constant J specimen for a constant load; the crack propagates in the mid-plane of the test specimen. This test is in the process of being approved by ASTM for testing for brittle materials. Report C00-2422-17 is the effort within this laboratory to see if a standardized procedure may be adopted by ASTM.

Report C00-2422-18 was prepared to relate the measured crack velocity to the true crack velocity in a double torsion test specimen. The fact

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that the crack front of a double torsion test specimen is not straight shows that the velocities in these samples are "averaged" over an order of magnitude. For several testing schemes, this is a problem - a straight crack front would be preferable.

4. Crack Driving Force versus Crack Area in Double Cantilevered Beam Specimens

In report C00-2422-10, the initial non-linear fracture paper, established that in linear elastic material there is always an "equation of state" that relates the crack driving force to the load and the load-point displacement of the specimen. In addition, there is a compliance relation that relates the crack area to the ratio of the load to the load-point displacement. In report C00-2422-19, the static compliance curve was experimentally measured for double cantilevered beam (DCB) specimens. Equations (6) and (8) are the analytic expressions, for DCB specimens, that relate the load and the load-point displacement to the crack driving force, J , and the crack area A . Figure 3 is a schematic of an analogue electronic box that receives an electronic voltage that is proportional to the load, P , on the DCB specimen and a second voltage that is proportional to the load-point displacement, X . The electronic box generates voltages proportional to J and A . i.e., it electronically generates the elastic, solution for the DCB specimen in Equations (6) and (8). Note that using this electronic box that J vs. ΔA can be plotted directly from measurements of P versus X . This has the advantage of being able to test specimens with nearly straight crack fronts (see C00-2422-18). However, the DCB specimen still has difficulty that the crack occasionally will run

Fig. 3. Elastic electronic solution for a double cantilevered beam specimen.

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out of the grooved mid-plane of the specimen. It also has the disadvantage that the test specimen must remain linear elastic to properly define the crack driving force. i.e., if the entire DCB specimen were creeping then the electronic box would not correctly generate the J value. In the creep case, a constant bending moment would have to be applied to the DCB specimen.

5. Crack Velocity Rate Dependence near the Brittle to Ductile Transition Temperature in Steel.

Report C00-2422-20 is an experimental study of the dependence of the critical, dynamic, stress intensity factor versus crack velocity (rate) and test temperature. We have experimentally found that as the brittle to ductile transition temperature in the steel is approached that the fracture rate dependence becomes larger. The rapidly wedged DCB specimen is unique for investigating fracture when the stress intensity value increases with decreasing rate. Most test specimens are unstable in this fracture region. The rapidly wedged DCB specimen is however, a difficult test because the DCB specimen does not always guide the crack down the mid-plane of the test specimen. For our test fixture, this means that the remaining part of the test specimen is crushed between the hammer and the base of the test fixture. In the steel we have tested, there is nearly an order of magnitude difference in the value of the slope of the crack driving force versus the fracture rate (velocity) between liquid nitrogen temperature and 0°C. Even at 0°C the fracture is still by brittle cleavage in these mild steel samples. The fracture surfaces at the highest test temperatures

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are still flat fractures and are thus thought to represent plane-strain values. At the present time, the rate-temperature-crack driving force below the brittle to ductile transition temperature is not an easy analysis since:

- A) There is very large experimental scatter in the test data.
- B) J_{IC} has a negative rate dependence and is therefore unstable.
- C) J_{IC} values are so large that linear elastic samples are often difficult to test especially near the brittle to ductile transition temperature.

The data reported in C00-2422-19 and 20 is therefore unique and will be significant in understanding the crack velocity (rate) versus temperature and crack driving force in the brittle fracture region especially near the brittle to ductile transition temperature.

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Personnel Connected with Contract:

- 1) Professional Staff: S. J. Burns (22%)
- 2) Research Assistants (Graduate Students):
 - J.-C. Pollet (100%)
 - B. Majumdar (100%)
 - P.W. Early (40%)

Oral Presentations

- S.J. Burns, "Fast Fracture: An Adiabatic Restriction on Thermally Activated Crack Propagation," ASTM Symposium on "Crack Arrest Methodology and Applications."
- S.J. Burns and C.-L. Chow, " K_{ID} Values Deduced from Shear Force Measurements on DCB Specimens," ASTM Symposium on "Crack Arrest Methodology and Applications."
- S.J. Burns, "Thermodynamics of Fracture," National Bureau of Standards - Deformation and Fracture Group - Washington, D.C.
- S.J. Burns, " J_{IC} Measured with Mechanically Unstable test Specimens with Finite Differences in Crack Areas," ASTM Elastic-Plastic Fracture Mechanics Committee.

Technical Reports and Articles

C00-2422-15

Corrections and Comments on the paper, "Non-linear Fracture Mechanics."

C00-2422-16

Two New Expressions for J.

C00-2422-17

Double Torsion Testing, Evaluation for ASTM E-24.07.02.

C00-2422-18

Crack Velocity Correction Factor for the Crack Front Shape in Double Torsion Specimens.

C00-2422-19

Rapidly Wedged Crack Propagation Data with a Static Compliance Calibration.

C00-2422-20

K_{ID} Values Deduced from Shear Force Measurements on DCB Specimens.

C00-2422-21

Fast Fracture: An Adiabatic Restriction on Thermally Activated Crack Propagation.

C00-2422-22

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