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Summary

There were 55 presentations on the program at the Seventeenth National ASTM Symposium on Fracture Mechanics. For a variety of reasons, all related to the technical and time pressures of preparing a submission to this sort of meeting and publication, 44 papers appear in this volume. At the symposium the presentations were divided into five categories: Applications, Subcritical Crack Growth, Fracture Testing, Ductile Fracture, and Analysis and Mechanisms. These categories, although somewhat arbitrary because of the broad scope of many of the papers, are used in this volume and summary. Only a few terms are defined here; the reader can easily refer to the appropriate paper.

Applications

The papers in this section are concerned with the application of fracture mechanics concepts to the analysis of fatigue crack growth and fracture behavior of metallic materials and to the analysis of fracture behavior of ceramic and composite materials.

Hilton et al used fracture mechanics analyses to establish the material fracture toughness requirements to avoid loss of a ship propeller blade. Using engineering approximations and a simple finite-element analysis of a particular propeller crank ring, a toughness value from a J_R resistance curve was established as a minimum requirement for 4150H steel material. The fact that a full-scale laboratory test on a 4150H crank ring did not experience unstable fracture showed that the analysis was conservative.

The paper by *Tanaka et al* presented a new wide-plate short-crack arrest (SCA) test specimen for testing steel weld joints at low temperatures. The basic idea for the development of the SCA test is that brittle fracture should be initiated at the center of a wide plate to eliminate the effects of high compressive residual stresses that exist in welded crack-arrest specimens with edge cracks. One advantage of the SCA test is that it simulates a surface defect which may exist in actual structures.

Yang and Bamford characterized the response of semi-elliptical surface cracks under thermal shock conditions which may result from safety injection actuation in nuclear reactor vessels. The authors developed a methodology to predict the growth behavior of such cracks under simulated thermal shock conditions. Results from the study showed that cracks tend to elongate along the vessel inside surface.

Fatigue crack growth tests on circumferential surface cracks in solid and hollow cylinders under remote tension and bending loads were conducted by *Forman and Shivakumar*. Tests were conducted on both aluminum and titanium alloy specimens. Results show that surface-crack shapes in solid cylinders can be accurately represented by a circular arc, whereas crack shapes for internal or external surface cracks in hollow cylinders can be represented by a transformed semi-ellipse. Stress-intensity factor expressions for surface cracks in hollow cylinders were presented.

The paper by *Bradley et al* studied the dynamic fracture behavior of ductile cast iron and cast steel using either blunt-notched or fatigue precracked (side-grooved) Charpy specimens. The blunt-notched specimens gave erroneous indications of the relative toughness of the two materials (ductile iron being quite inferior to cast steel), whereas the precracked and side-grooved specimens showed that the ductile iron was actually superior to cast steel at temperatures below ambient. The differences in these results were attributed to variations in constraint through the thickness.

The effect of loading rate on the dynamic fracture of reaction-bonded silicon nitride (RBSN) was presented by *Liaw et al.* A novel experimental-numerical procedure, where the experimentally determined crack extension history drives a finite-element code in its generation mode, was used in the study. One of the major findings was that a crack in RSBN can continue to propagate at its terminal velocity under a low dynamic stress-intensity factor.

The last three papers in this section dealt with the fracture behavior of composite materials. *Ratwani and Deo* used the resistance curve approach to characterize the delamination growth resistance of various composite material systems. They found that the delamination growth resistance curves were a function of the resin material as well as the fiber used. *Harris and Morris* compared the fracture behavior of thick graphite-epoxy laminates using standard fracture toughness specimens (compact, three-point bend, and center-cracked tension). Fracture toughness values computed using the load at the intersection of the 5% secant line with the load-COD (crack-opening displacement) record were found to be independent of laminate thickness and specimen configuration. The paper by *Simonds* studied the residual strength of five boron/aluminum laminates with sharp notches with and without prior fatigue loading. Although the fatigue loading (60 to 80% of the static tensile strength) for about 100 000 cycles caused some matrix and fiber cracking, the residual strength was not significantly affected by the prior fatigue loading.

Subcritical Crack Growth

Most of the attention on the subject of fatigue crack propagation rates (FCPR) has been devoted to behavior at ambient temperature under constant-frequency, constant-amplitude conditions. This session delves deeper into the factors that influence FCPR. It also evaluates some interesting techniques for monitoring crack growth behavior.

Nicholas and Weerasooriya examined hold time effects on FCPR at elevated temperatures. Using Inconel 718 and studying the constant K behavior at 650°C, the authors showed that the hold times at maximum load displayed the greatest FCPR. Also, at maximum load hold times greater than 5 s, FCPR was time dependent. A linear cumulative damage model based solely on fatigue and sustained load data was found to be adequate for spectrum loading as long as the hold times were at maximum load. Also evaluating Inconel 718 at 650°C were *Petrovich et al.* They were able to detail the interactive effects of low and high frequency cycling on FCPR. It is interesting that as high-frequency ΔK is combined with constant low-frequency ΔK, two regions of FCPR behavior are noted: one where low frequency cycles dominate and the other where high frequency cycling governs. In the former, a retardation effect which is strongly dependent on low-cycle ΔK is noted.

Saxena studied crack growth under high temperature non-steady-state conditions. He described a crack parameter C_t which correlated well with da/dt under conditions that range from small scale creep to the steady-state creep regime. The correlation appears to be independent of specimen geometry. It was shown that for A470 Class 8 steel, da/dt as a function of C_t is independent of temperature in the range of 482 to 538°C to a first-order approximation.

Soya et al addressed the fatigue behavior of welded Invar sheet in the cryogenic temperature region. An equivalent stress intensity factor, K_{eq}, was calculated from $(K_I^2 + K_{II}^2)^{1/2}$ and was based on a finite element analysis of elastic and elastic-plastic conditions that exist at the weld root. K_{eq}, plotted versus the number of cycles to failure, can be utilized in the same manner as the traditional *S-N* curve. In the temperature range between room temperature and -162°C, for several types of fillet joints and one type of seam weld, it was shown that K_{eq} can be used to normalize the cycles-to-failure data in the region where large plastic deformation is not a factor ($<10^4$ cycles).

Several novel techniques for monitoring crack growth behavior complement the efforts noted above. *Larsen* reported the development of an automated photomicroscope system for monitoring the initiation and growth of small surface cracks. Behavior of surface cracks in the 25 to 2000 μm range was studied. Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) was used to evaluate the system, which had a precision of about 1 μm for cracks of about 25 μm in length. It is noted that this method can provide a cost-effective means of monitoring growth of small cracks.

The growth and coalescence of small cracks was the subject of a paper by *Grandt et al.* A multiple degree of freedom algorithm is utilized to predict the growth of separate cracks. The crack shapes and sizes are then allowed to develop naturally as they join into a simple flow. The analysis was confirmed by the use of heat-tinting techniques on Waspaloy and Tl-6246 alloys.

Sharpe and Lee described an experimental study of crack tip displacement during high-temperature cyclic loading of Inconel 718. At the heart of the technique is a laser-based interferometer that detects fringe patterns produced from two microhardness indentations. Tests conducted between 23 and 650°C showed that compliances were in reasonable agreement with analytical predictions. Opening load ratios were found to be independent of temperature, crack length, and precracking level when measured at positions more than half the specimen thickness away from the crack tip.

The paper by *Wilson and Palazotto* also concentrated on crack-tip behavior utilizing IN-100 compact tension specimens cycled at 732°C. Viscoplastic constitutive equations are utilized in an analysis of the stress and strain field around the crack tip. It was interesting to note that most of the plastic straining occur within the first 3 cycles and that after about 23 cycles the material will no longer undergo any more plastic strain increase. After 1 to 3 cycles, the strain field ahead of the crack remains relatively constant.

Fracture Testing

The following papers were included in Session III of the symposium, held to honor Dr. John E. Srawley and Mr. William F. Brown, Jr. In their long association with the NASA-Lewis Research Center, these two researchers have made truly significant contributions to the area of fracture mechanics test methods. This session, which they chaired, was a tribute to them as they ended their full time work in the field of fracture.

The first three papers described opening mode fracture toughness testing using new test geometries. *Underwood et al* give recommendations for practical arc bend specimen geometries. Solutions are presented for stress intensity, crack mouth displacement, and load-line displacement for fracture specimens that have been compared using finite element and boundary collocation techniques. *Kapp and Bilinsky* described J_{Ic} tests in aluminum and steel alloys using the new arc-tension specimen and the existing compact specimen. A Merkle-Corten type analysis was presented for calculating J for the new specimen. The results showed that the specimen and methods of J analysis are suitable for accurate determination of J_{Ic}, and it is suggested that this information be added to the ASTM J_{Ic} test method. The paper by *Giovanola* shows the influence of specimen dimensions and impact velocity on dynamic fracture toughness of an edge-cracked coupon loaded in bending and impacted at midsection. This new procedure was used to measure the toughness of 4340 steel at three loading rates. The relative advantages of this one-point-bend test in dynamic fracture testing are indicated.

Two papers were presented on Mode II fracture testing. *Buzzard et al* described a test specimen that was developed to obtain fatigue crack propagation data under Mode II shear loading. Stress intensity factor and displacement analyses were performed and compared with photoelastic stress analysis. These results and the nature of the observed fatigue crack growth data suggested that the specimen and analysis would be adequate for Mode II fatigue testing. *Banks-Sills and Arcan* used a finite element analysis of a compact K_{II} specimen and load frame geometry to determine Mode II critical stress intensities. Mode II toughness tests of polymethyl methacrylate (PMMA) indicated that K_{Ic} was greater than K_{IIc} and that the average Mode II crack extension angle occurred along the direction of maximum tangential stress, which was between 63 to 70°.

The last three papers dealt with *J-R* curve testing. *Sutton and Vassilaros* presented comparative data for *J*-integral resistance curves for ASTM Class C and 3-Ni steels, using two reference techniques, multispecimen and d-c potential drop, for comparison with elastic compliance. The *J-R* curves established using elastic compliance showed no significant difference from the reference curve data. In the paper by *Davies and Stearns* the d-c potential drop technique was shown to be unacceptable for measuring the fracture toughness of Zircaloy-2 in the brittle-ductile fracture transition. The potential drop underestimated crack extension by 60%, increasing to 100% at higher test temperatures. Reproducible results were obtained using individual specimen calibrations.

Kapp and Jolles performed *J-R* tests of two aluminum and three steel alloys using Charpy size bend specimens and larger, standard compact specimens. Load-drop and electric-potential methods of crack growth were used. Based on comparisons of results from the two types of specimens and crack growth, the load-drop method with small bend specimens resulted in approximate *J-R* curves which would be suitable for quality control fracture toughness tests.

Ductile Fracture

There were two general groups of papers in this session of the symposium, one emphasizing test methods and results and the other emphasizing the mechanisms of ductile fracture.

Test Methods and Results

Three papers dealt primarily with ductile fracture test methods and results. *Hirano et al* described a single-specimen ultrasonic method for obtaining *J* versus crack growth curves. Measurements of J_{Ic} and tearing modulus in A533B steel were found to be independent of specimen geometry. It was also observed that the crack tip opening displacement (CTOD) remained nearly constant during stable crack growth. *Vassilaros et al* obtained *J-R* curves using compact specimens from A106 steel pipe and compared the results with those from four-point bend tests of 4-ft lengths of 8-in.-diameter pipe. The general result of the comparison was that the small specimen tests do not directly predict the *J-R* curve behavior of full size pipe because of the small amount of crack growth available in the specimen tests. *Towers and Garwood* described J-integral and CTOD analysis of bend tests of HY130 steel. Since these are the two most accepted methods of analysis for ductile fracture, this comparison of results is particularly interesting. In general, the two methods agree in their description of resistance to ductile tearing. Both methods indicate greater tearing resistance for shallower cracks (i.e., for a/w of 0.1 to 0.2 compared with 0.5).

Mechanisms

Four papers dealt primarily with ductile fracture mechanisms. *Etemad and Turner* investigated ductile tearing mechanisms using experiments with HY130 steel and analyses of energy rate, I, and tearing modulus, dJ/da. In the authors' words: "Subject to the choice of appropriate compliance terms the experimental behavior is predicted satisfactorily by both I and dJ/da methods." The authors also stated that satisfactory predictions are restricted to the geometry for which the R-curve was obtained. *Carifo et al* discussed finite element computation of stable crack growth using techniques of element node release. Conditions for nodal release are described and demonstrated in a series of finite element models of stable crack growth. *Hackett et al* investigated environmentally assisted crack growth of 4340 steel in seawater using techniques developed for the study of stable elastic-plastic crack growth. The authors found that J-R curves could be used for this different purpose, provided the rate dependence of the environmentally controlled process is considered. They observed a significant (four-fold) decrease in the energy required for crack initiation, J_{Ic}, due to cathodic polarization of the specimens. *Watson and Jolles* investigated global plastic energy dissipation for crack initiation and growth using experiments with HY130 steel for a variety of specimen configurations. Specimen size, specimen type, crack length, and side grooving were studied. R-curves using plastic energy dissipation (rather than J) showed some geometry dependence, which was minimized using side grooves.

Analysis and Mechanisms

The papers presented on the last day of the symposium focused primarily upon determination of loading and geometric (body shape) effects upon fracture parameters or upon determination of near tip material response. Included in this session was an overview lecture by Dr. George Irwin on Progressive Fracture Mechanics, in which he traced developments over several decades up to the present time. The range of time and technical topic in the lecture covered all aspects of fracture, including analyses, experiments, and applications.

The first paper of the session was that of *Pu*, which addressed the problem of an array of unequal depth radial cracks at the inner radius of a pressurized cylinder. The author used quadrilateral finite elements and collapsed singular elements around the crack tip to calculate stress intensity factor for a number of cases. The general result was that a crack which was slightly deeper than others in the array had a significantly higher K value, so that the deeper crack quickly dominated.

Sha and Yang described a method for computing stress intensity factors by combining the uncracked stress field with explicit crack face weight functions through superposition. The method was illustrated by applying it to the problem of symmetric radial cracks emanating from a circular hole in a plate. *Yau* presented a surface crack solution for fatigue crack propagation analysis of notched components. The solution was based on the weight function technique and was compared with a wide range of test results. Good agreement was observed between experimental results and analytical predictions, including such key information as stress intensity factor, crack propagation rate, residual life, and variation in crack shape.

A paper by *Müller et al* presented results of an analytical and experimental study of surface crack growth under cyclic loading. The authors found that use of local ΔK values gave a poor prediction of the crack aspect ratio, while use of a weighted average ΔK or a crack closure factor improved predictions. *Reuter* presented results of a combined analytical-experimental study of crack growth initiation under elastic and plastic conditions. A modified center cracked panel equation was used in the predictions, and acoustic emission methods were used to detect the load corresponding to crack initiation. The author presented evidence which questions the usefulness of J_{Ic} in structures where J-controlled fields are not attainable. Next, *Balladon and Heritier* compared the fracture toughness and crack growth properties of three grades (316L, 347, and austero-ferritic) of steel at room and elevated temperatures. Comparisons were based on the J-integral concept. Variations observed could not be explained solely on the basis of inclusion content and crack plane orientation.

Homma et al performed experiments in steel and aluminum to measure the minimum time duration at load which is required before a crack grows in an unstable manner. The relation between the minimum times obtained for the materials and their mechanical properties was discussed. The experimental results showed that the minimum time is longer for the more ductile materials. *Shukla and Anand* reported on the results of dynamic photo-elastic experiments under remote biaxial stress fields. They found that while the normal stress parallel to the crack surface had negligible influence on the branching stress intensity factor and crack velocity, a strong influence of the parallel stress was observed on the branching angle.

Next, *Anderson and Williams* used the results of a large number of crack-tip opening displacement (CTOD) measurements on carbon-manganese steels (using single edge notch bending and tensile tests) to assess the dominant mechanism for size effects on CTOD values in the ductile-brittle transition region. The authors concluded that, under conditions of small-scale yielding, a high constraint statistical sampling model works well for explaining size effects. When net section yielding occurs, however, statistical effects are suppressed and size effects are dominated by constraint effects. *Joyce and Hackett* described a series of J-integral R-curve tests on three-point-bend steel specimens at three different load rates. Through the use of multispecimen and key curve procedures at the higher rates, the authors found that J_{Ic} values and tearing modulus (T) values were elevated at the higher loading rates. The J_{Ic} and T values were increased by a factor of approximately two for a loading rate increase of six orders of magnitude.

Smith et al presented a quantitative evaluation of the loss of the inverse square root singularity when a crack intersects a free surface at right angles in nearly incompressible materials. Compact bending and surface flaw specimens were tested using frozen stress photoelasticity and moiré interferometry. After correlating free surface results with analytical results, the authors measured the variation of the lowest eigenvalue through the thickness and found thicker transition zones than previously suspected. The session was closed with a paper by *Raju and Newman* in which they utilized a refined three-dimensional finite element model to study surface flaws. The authors employed singularity elements along the crack front and linear stress elements elsewhere to obtain the stress intensity distribution along flaws in pipes and rods under extension and bending. Results from the models, which contained 6500 degrees of freedom, compared favorably with analyses and experiments of others.

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