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Summary

Since the discovery of fatigue-crack closure in 1968, a sometimes cyclic enthusiasm on the subject has produced many publications. A simple summary of the nearly 20 years of research would be that rational crack-growth analyses cannot be performed without consideration of closure, but closure concepts alone cannot explain all crack-growth characteristics. Also, most researchers would agree that while direct measurement of opening and closing loads would be ideal, none of the many techniques proposed have reached a level of confidence for standardization. While the recognition of the phenomenon has improved our understanding of the cracking process, closure considerations have vastly increased the complexity of modelling crack growth. The objective of the symposium and of this book is to advance the state of the art in the mechanics of fatigue-crack closure.

The papers in this publication have been divided into four sections: Mechanisms, Measurements, Analyses, and Applications. In the first section, the various mechanisms of crack closure are reviewed, and the crack-growth regimes where they are important are discussed. Next, the measurement techniques that are currently used to measure crack-opening and closing loads are presented. Some of these papers define ways of standardizing closure measurements. In the analysis section, several papers are presented on finite-element analyses of the crack growth and closure process. Other papers are concerned with the application of simple models of crack closure such as the ligament or strip-yield models. Crack-closure concepts have been extremely useful in many practical applications such as the correlation of crack-growth rate data and for predicting crack growth under variable-amplitude loading. The application section demonstrates how the crack-closure concept can be used to improve damage-tolerance analyses.

Mechanisms

Some of the most promising new mechanisms of fatigue-crack closure have been discovered in the last few years. While earlier research was solely concerned with plasticity-induced closure, the other mechanisms of closure, such as crack-surface roughness, oxidation, and bridging have brought some new insight into the influence of microstructure and environment on the cracking process. These important observations and the technical significance of crack closure, especially for variable-amplitude loading, were discussed by Schijve in his keynote paper.

McEvily discussed the relative importance of several forms of closure mechanisms. They were plasticity-induced, roughness-induced, crack-filling-induced, material-transformation-induced, and grain-boundary-induced closure. He also discussed the load-interaction effects or "transitional" closure effects on crack growth. On the basis of his review, he concluded that plasticity-induced closure plays a relatively minor role in affecting the growth of cracks except during overloads.

On the other hand, Davidson, and Hudak and Davidson, conducted extensive experimental measurements of "plasticity-induced" closure on 7091-T7E69 aluminum alloy and

304 stainless steel under constant-amplitude loading using a high resolution microscopy technique (scanning-electron and optical microscope). For tests conducted at low values of stress-intensity factor ΔK and at a stress ratio R of 0.1, crack-opening loads were determined by observing the crack-tip region on the surface of single-edge-crack specimens. Extremely high values of P_o/P_{max} were measured (0.6 to 0.9) under opening-mode (Mode I) conditions. The opening-load ratio was found to be a strong function of ΔK. Comparisons made with two analytical closure models (Budiansky-Hutchinson and Newman) indicated that the models were deficient. The Budiansky-Hutchinson model predicted a ΔK-independent crack-opening load ratio. Whereas, the Newman model predicts crack-opening (displacement) profiles similar to those observed experimentally, the model also predicts nearly a single value of opening-load ratio for the range of ΔK values considered. Obviously, more research is needed to explain the differences between experiments and analytical models. The extremely high crack-opening-load ratiös observed experimentally may be due to a three-dimensional effect (see Hudak and Davidson, and Chermahini et al., in this book).

An overview of crack-closure behavior in the near-threshold regime was presented by Liaw. He concluded that crack-closure concepts generally rationalize the influence of microstructure, environment, loading condition, and crack size on near-threshold fatigue-crack growth. Improvements in crack-growth resistance of dual-phase steels and grain-size effects can be rationalized by roughness-induced closure and crack deflection. Oxide-induced closure accounts for the yield-strength effect on ΔK_{th}. Growth of small cracks below large-crack thresholds was caused by lower closure levels for small cracks. However, some growth characteristics, such as the effect of cryogenic temperatures on ΔK_{th}, could not be explained by closure. To improve fatigue-life prediction methods, analytical closure models need to be developed to account for roughness-, oxide-, and phase-transformation-induced closure.

Ward-Close and Ritchie studied the transient fatigue-crack growth behavior following a tensile overload at low and high stress-intensity factor ranges in IMI 550 titanium alloy. An initial crack-growth acceleration, after a tensile overload, was attributed to an immediate reduction in *near-tip* closure, as indicated by metallographic sectioning, and a slight decrease in far-field closure, as measured by back-face compliance methods. Subsequent retardation was not associated with marked changes in far-field closure, although there were indications on compliance curves of a second "closure point" at a higher load, suggesting about a 50% increase in near-tip closure. These results suggest that "far-field" compliance methods may not be sensitive enough to measure "near-tip" closure effects during overloads. (Can this be why Turner et al., in this book, did not see any closure after a high R-ratio overload?)

The effects of test frequency and asperities on crack closure were discussed by Sheth and Gerberich. In single crystals of an Fe-Si alloy, increased frequency caused an increase in surface roughness (larger steps on the crack surfaces) and larger K values at opening K_{op}. The effective stress-intensity factor concept alone, however, was not able to explain the observed decrease in growth rate with increasing test frequency.

Hertzberg et al. presented a reevaluation of the ΔK-decreasing (constant stress ratio) test procedure. They concluded that this method may introduce abnormally high closure levels and generate nonconservative values of ΔK_{th}. Furthermore, they also conclude that at least part of the difference between long and short crack-growth-rate data may be traced to anomalously low growth rates associated with long cracks. (Movements are currently underway in the aerospace community to reduce the ΔK_{th} values obtained from load-shedding long-crack tests.)

The crack-closure mechanism has been extremely useful in explaining most of the differences between growth rates for small and large cracks. Larsen et al. used a computer-controlled photomicroscopic system with an automated laser-interferometric technique to monitor crack growth and closure of "small" surface cracks. The effective stress-intensity factor concept consolidated growth-rate data on three titanium-rich Ti-Al alloys quite well for a wide range in stress ratios and stress levels. This finding is significant because it indicates that much of the "anomalously" rapid growth of microstructurally small cracks may be associated with crack-closure effects rather than crystallographic anisotropy in the region of the crack tip. The band of data for small cracks, however, generally gave higher rates for a given ΔK_{eff} than those measured on large cracks in compact specimens. This may indicate that microstructure is affecting the absolute rate for small cracks (rates for large cracks are "average" rates through many grains).

Measurements

A large number of techniques have been proposed for measuring the load at which a crack front opens or closes. Because the crack front does not open at a single load, the search for an ideal measurement technique has been very frustrating. Several researchers have proposed to "standardize" a technique to eliminate disagreement. However, it would be premature to standardize on a technique, which still has inherent errors, only for the sake of repeatability. Many researchers still measure the "closure" load during the unloading of a specimen. Although in many cases the "closure" load may be nearly equal to the "opening" load, in general, the loads are different, especially at high loads. The editors believe that the "opening" load should be measured instead of the "closure" load.

Allison et al. made comparisons of three experimental techniques to measure crack-opening loads on compact specimens made of two titanium alloys with different microstructural conditions. Two "global" compliance techniques (crack-mouth-opening displacement and back-face strain) and a near crack-tip surface technique (two-stage replication) were studied. Several different numerical procedures for determining the inflection point (opening load) in the load-displacement record were evaluated. In experiments at low stress intensities, all techniques gave similar opening loads. The replication technique demonstrated that asperity-induced closure was predominant in the β-processed microstructure (crack-tip region remained open at zero load), whereas cracks in the α/β-processed microstructure were closed.

The effects of simple load histories and compact specimen size on closure measurements were presented by Ashbaugh. Again, three methods were used to measure K values at closure, K_{cl}, on Rene' 95 (a powder metallurgy nickel-base superalloy). They were (1) clip gage at crack mouth (CMOD), (2) back-face strain (BFS) gage, and (3) laser-interferometric-displacement gage (IDG). The far-field closure values from the IDG were consistent with those obtained from the BFS and CMOD techniques. Results indicate that values of K_{cl} were dependent on measurement location. Closure values were also strongly dependent on specimen dimensions (crack length, width, and thickness). See the paper by Zawada and Nicholas for more results on Rene' 95.

Ray and Grandt also used three techniques to measure crack-opening loads on four-point bend specimens made of polymethylmethacrylate (PMMA). An optical interferometry method, in addition to the BFS and CMOD techniques, was used. In contrast to the "global" techniques, the interferometry method provided a complete three-dimensional crack-surface displacement pattern. Closure loads from the BFS and CMOD measurements agreed well but were lower than the interferometric free-surface values. Mid-plane displacement profiles obtained from a two-dimensional, elastic, finite-element analysis of a stationary crack agreed well with the experimental results from the optical interference method.

Carmen et al. presented a combined experimental and analytical method to determine the crack-opening loads from load-displacement records. The load-displacement trace on loading was assumed to be composed of a linear portion at low loads, a quadratic relation before opening load, and a linear portion from opening to maximum load. A nonlinear, least-squares routine was used to best-fit the analytical curves to experimental data on 7475-T731 aluminum alloy middle-crack tension specimens. The proposed method provided a consistent, automated method for determining the opening loads from load-displacement records.

A procedure for standardizing crack-closure measurements was presented by Donald. A commonly used method for determining crack-opening loads is the load-reduced-displacement method. However, the interpretation of the opening load from a "reduced" load-displacement curve may be tedious, subjective, and nonrepeatable. Donald has proposed a consistent and automated method to determine an "opening" load. A 2% change in the slope from the unloading slope was suggested. The method was demonstrated by correlating crack-growth rate data on 2219-T851 and 2024-T351 aluminum alloys.

Roberson and Kirk approached the determination of crack-opening loads in high-strength steel weldments by a statistical method. Opening loads were defined by using a statistical test to consistently determine deviations from linearity on the upper portion of the load-displacement record. By systematically accounting for test-dependent data scatter or "noise" a consistent definition of opening load was achieved.

Foroughi and Radon used two compliance techniques to study crack-closure behavior of surface cracks in a structural steel under pure bending. Crack closure at the intersection of the crack front with the free surface was monitored by use of an Elber-type gage, whereas "bulk" closure behavior was determined by means of a standard clip gage at the crack mouth. Under constant-amplitude loading, the crack-opening load at the surface-intersection point was considerably higher than the bulk opening load. For a wide range of stress ratios, crack-growth rate data at the surface-intersection point expressed in terms of the "effective" stress-intensity factor range correlated the data.

The last three papers in this section are concerned with the closure behavior of small (or short) cracks. Lee and Sharpe used the laser-interferometric-strain/displacement gage (ISDG) to measure crack-opening loads for short cracks, as short as 35 μm, in 2024-T3 aluminum alloy sheet material. The specimen and the loading conditions tested were part of an AGARD-sponsored, round-robin test program designed to study the growth of short cracks. The opening loads measured with the ISDG for short cracks were equal to or less than those calculated from Newman's modified Dugdale model for long cracks. The differences were significantly larger for negative stress ratios ($R = -1$ and -2). These results support the concept that the rapid growth of short cracks is due primarily to the "lack of closure."

McClung and Sehitoglu measured the closure behavior of small cracks under high-cyclic-strain histories in Society of Automotive Engineers (SAE) 1026 steel. The nominal stress ratio was -1. They used a two-stage replication technique to identify the load level at which the crack tip opens and closes. The normalized crack-opening levels were observed to decrease with increasing strain amplitude. Results compared favorably with the modified Dugdale model analysis of Newman. Closing levels were significantly lower than opening loads at high strain amplitudes. Correlation of crack-growth rate data using ΔJ and ΔCTOD were more successful when "effective" stress ranges were used.

Ritchie et al. studied the development of fatigue-crack closure for long and short cracks in 2124-T351 aluminum alloy. These measurements were compared with those calculated from elastic-plastic, finite-element analyses under plane-strain conditions. The numerical analyses consistently underpredicted the magnitude of closure, especially near-threshold conditions. In the experiments, significant additional closure arises from the wedging action of asperities and corrosion debris, whereas the analysis considered only plasticity-induced closure. Future analytical studies should incorporate these additional forms of closure.

Analyses

Fleck and Newman used a two-dimensional, elastic-plastic, finite-element analysis to study crack-closure behavior under plane-strain conditions. They concluded that plasticity-induced closure only occurs during a transient period when a crack evolves from a stationary state (initial crack) to a steady-state condition of a growing fatigue crack. In a center-cracked panel at a stress ratio of zero, the opening-load ratio P_o/P_{max} peaked at about 0.3, but with further crack advance the ratio fell steadily to about 0.2. Here the crack surfaces displayed discontinuous closure with the crack-tip region remaining open. The transient behavior predicted by their analysis may be important in laboratory experiments where "steady state" plane-strain conditions can not be achieved.

Lalor and Sehitoglu also used a two-dimensional, elasto-plastic, finite-element analysis to study the growth of cracks from circular holes under both plane-stress and plane-strain conditions for large-scale yielding. Under constant-amplitude loading, the crack-opening stress levels were found to vary as a function of stress ratio, stress level, stress state, and crack length. Crack-opening stress levels tended to stabilize as the crack length increased. This paper demonstrated that crack-opening stresses may be negative under fully reversed loading for large applied stress levels. These results may be useful for explaining the growth of short cracks from holes where the applied stress levels are large.

A further study on the closure behavior of "short" cracks was performed by Nicholas et al., again using an elastic-plastic finite-element method. Their results confirmed that some short-crack effects may be explained by a "lack of closure." They also demonstrated, by calculation, how crack-opening loads should be determined, experimentally, from load-displacement records.

The paper by Anquez and Baudin deals with a two-dimensional (plane stress) elasto-plastic finite-element analysis to predict crack-opening stresses under constant-amplitude and two-level block loading. Comparisons made between calculated and experimental crack-opening loads were quite good.

The first three-dimensional analysis of fatigue-crack closure was presented by Chermahini et al. Their paper was concerned primarily with describing the assumptions made in the elastic-plastic finite-element analysis. A specimen configuration used in an ASTM round-robin on crack closure (currently in progress) was analyzed on the computer. The results from this paper showed similar characteristics to those presented by Fleck and Newman (in this book) for the interior of the specimen but gave results on the exterior that were similar to previous plane-stress calculations.

Keyvanfar and Nelson developed a new type of ligament model to study crack-closure effects in a wide variety of crack configurations. The original ligament model, developed by Newman, was restricted to a double-edge-crack configuration. The improved ligament model (ILM) was successfully applied to a crack growing near and through a residual-stress field caused by a weld.

The papers by DeKoning and Liefting, Nakamura and Kobayashi, and Nisitani and Chen are applications of modified Dugdale (-Barenblatt) or strip-yield models to study crack-closure behavior. In the first paper, the strip-yield model was developed specifically to improve an empirical crack growth and closure model (referred to as CORPUS). Both models were successfully applied to predict crack growth under a flight-by-flight block-program loading for a landing gear. The second paper examined the influence of asperities on crack-closure behavior using the modified Dugdale model proposed by Newman. The effects of asperity rigidity, length, thickness, and distance from the crack tip are presented. In the last paper, a new method of obtaining the "closure load" was developed in which plastic deformations near the crack tip are taken into consideration. Using the modified Dugdale model, as proposed by Budiansky and Hutchinson, the analyses suggest that the crack opening and closure loads can be determined, experimentally, by measuring the local stress-strain hysteresis. The new method was successfully used to correlate crack-growth rate data on a carbon steel. Whereas, crack-growth rate data expressed in terms of the elastic stress-intensity factor range showed a "threshold," the same data expressed in terms of the effective stress-intensity factor range did not exhibit a threshold.

Applications

Aliaga et al. have presented an empirical crack-closure model (PREFFAS) to predict crack growth under various aircraft fatigue spectra (TWIST, Mini-TWIST, and FALSTAFF). The model requires three parameters that are determined from two simple crack-growth tests. Two parameters are obtained from the crack-growth power law (coefficient and power) and the last parameter is obtained from the P_o/P_{max} ratio at a stress ratio of zero. The model combines a cycle-by-cycle analysis with a cycle counting method similar to the "rain flow" method. Predicted crack-length-against-flights agreed well with experimental data on 2124-T351 aluminum alloy.

Phillips studied the development of thresholds and closure behavior in a 2024-T3 aluminum alloy sheet material for a wide range of stress ratios ($-2 \leq R \leq 0.7$). Crack-opening loads were measured using a remote displacement gage and were determined from the load-reduced-displacement technique. The effective stress-intensity factor range concept correlated the crack-growth rate data quite well, even at the threshold condition. In contrast to the carbon steel data (Nisitani and Chen), the aluminum alloy exhibited an "effective" stress-intensity factor threshold.

Similarily, Booth and Maddox correlated fatigue-crack growth rate data at different stress ratios ($-4 \leq R \leq 0.67$) for three structural steels ranging in thickness from 5 to 12 mm. "Crack-closure" stresses were determined from a strain gage located behind the crack tip. Plots of closure stress against distance from the crack tip were then used to extrapolate the closure stress at the crack tip. For $R \geq 0.5$, the cracks were fully open (no closure). The effective stress-intensity factor range concept correlated rate data quite well, but some discrepancies were observed at high R ratios for two of the steels.

Fatigue crack-growth delays after an overload during high-stress ratio constant-amplitude tests ($R = 0.7$) were investigated by Turner et al. Using a remote displacement gage, they found no closure before, during, or after the overload. However, they did observe delayed growth of the crack. They suggest that the delay was caused by reinitiation of the crack, possibly as a result of crack-tip blunting. (In contrast, the closure models, such as the modified Dugdale model, do predict that retarded growth will occur after a high R-ratio overload. This retarded growth is due to a rise in the calculated crack-opening stresses. Thus, further study is needed to clarify this discrepancy between experiments and analyses.)

The Buck et al. paper briefly reviewed the status of the experimental and theoretical research on the interaction of ultrasound with a partially closed fatigue crack. Significant progress has been achieved in the interaction of acoustic signals of partially closed cracks. This information makes possible a determination of the size and density of contacting asperities. Thus, the residual "contact" stress and the effective stress-intensity factor range can be determined.

Zawada and Nicholas conducted an experimental study on the near-threshold fatigue-crack growth and closure behavior of a nickel-base superalloy (Rene' 95) at 650°C. The first phase studied the effect of load history by applying three different load shedding rates to determine threshold values. Tests indicated no apparent influence of the particular shedding rates on threshold values. The second phase studied the effect of specimen width and thickness on crack growth and closure levels in the near-threshold regime. Threshold tests were conducted on various width (W = 20 to 40 mm) compact specimens with thicknesses ranging from 2 to 10 mm. Closure loads were determined from the "unloading" traces by using a load-differential-displacement technique. Test indicated no specimen thickness effect on closure K values K_{cl}, but there was an unexplained specimen width effect. The large-width compact specimen gave significantly higher K_{cl} values than the small-width specimen. The last phase investigated the influence of environment (lab air and vacuum) on near-threshold growth rates and threshold values. Although growth rates and thresholds were affected by environment, the K_{cl} values were nearly constant with K_{max} and were nearly the same for both environments. This paper deduced that the primary closure mechanism in this material was caused by roughness.

Telesman and Fisher studied the influence of plastic wake and surface-layer removal on K values at closure K_{cl}. Closure loads were taken at the first deviation from linearity in the unloading portion of the load-displacement record using a remote displacement gage. K values at closure were found to be about equal to those at opening. Compact specimens made of 3.2-mm-thick 7075-T6 aluminum alloy sheet were tested at a stress ratio of 0.1 with low, medium, and high stress-intensity factor ranges ΔK. The low value was near threshold. Plastic-wake removal did not influence K_{cl} at the medium and high ΔK values, even when the wake was removed within 0.5 mm of the crack front. But the tests near threshold showed that K_{cl} was affected by the wake removal. In contrast, the surface-layer removal experiments showed that the K_{cl} values for the medium and high ΔK tests were strongly influenced by removing the outside surface layers, whereas K_{cl} for tests at low ΔK were not affected. The authors conclude that crack closure in these tests were controlled by two distinct mechanisms, roughness and plasticity, roughness being dominant near threshold and plasticity controlling at high ΔK levels. More research is needed to understand the transition from roughness to plasticity-induced closure.

The last three papers in this section are concerned primarily with the closure behavior of surface-cracked specimens. Clerivet and Bathias conducted fatigue-crack growth and closure tests on center-crack tension, compact, and surface-crack specimens made of 2124-T351 aluminum alloy. Both remote and local displacement gages were used to determine bulk and near-surface crack-opening loads, respectively. Crack-opening loads from bulk measurements were assumed to be those for a "plane-strain" state, whereas local values were for a "plane-stress" state. Crack-growth data at R = 0.01 and 0.5 on surface-crack specimens were correlated quite well on a ΔK_{eff} plot using the "plane-strain" relation at the deepest point with the Raju-Newman K equations. However, an apparent stress-level effect was observed in the crack-growth rate data at the free-surface location. This stress-level effect was attributed to differences in crack-front shapes. Using three-dimensional stress-intensity factor calculations from Labourdette, the data at the free-surface location correlated with each other and agreed well with data from center-crack tension specimens. Further tests on surface-crack specimens under single spike overloads confirmed that ΔK_{eff} could account for the load-interaction effects.

Thoha et al. used an interferometry system to map the crack-opening displacement profiles for various surface cracks under bending in PMMA at a stress ratio of zero. Load shedding was used in the tests to maintain a constant stress-intensity factor range at the free-surface location. This study identified three types of crack-opening displacement patterns. Each type was associated with a particular crack-depth-to-thickness a/t ratio. The first type was a "fully" closed surface crack at zero load, and this type was found at a/t values less than

0.1. The second type exhibited an "open" region in the middle of the crack-surface area. All crack-front regions were closed at zero load. For a/t greater than 0.15, the third type showed that the region around the maximum crack-depth location was open at zero load. Only the region around the free-surface location was closed. During these tests, the P_o/P_{max} ratios at the free-surface location varied linearly with a/t and ranged from 0.25 to 0.35 for $0.05 < a/t < 0.4$. At the maximum crack-depth location, the P_o/P_{max} ratio started at 0.25 and rapidly dropped to zero when the a/t ratio reached 0.15. Although the application of these results to other materials is unknown, the results appear to be consistent with results published on metallic materials. Thus, these results should provide guidance for interpretation of experimental data and for analytical studies on surface cracks.

The last paper in this section was concerned with crack growth and closure behavior of "small" surface cracks in a high-strength titanium alloy. Jira et al. used the laser-interferometric displacement gage to study closure behavior in Ti-6Al-2Sn-4Zr-6Mo titanium alloy at stress ratios of 0.5, 0.1, and −1 and for a wide range in applied stress levels. The applied stress-intensity factor range correlated crack-growth rate data for $R = 0.1$ and -1, but the $R = 0.5$ data fell along a separate band. However, the effective stress-intensity factor range, determined from closure data, consolidated most of the data into a single band, but some small-crack data fell outside the band. Crack-surface roughness and plasticity were concluded to be the primary mechanisms contributing to crack closure.

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