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Microtopography For Ductile Fracture Process Characterization
Part 1: Theory And Methodology

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Part 1: Theory and Methodology

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Abstract

The mechanics of ductile fracture is receiving increased focus as the importance of integrity of structures constructed from ductile materials is increasing. The non-linear, irreversible mechanical response of ductile materials makes generalized models of ductile cracking very difficult to develop. Therefore, research and testing of ductile fracture have taken a path leading to deformation-based parameters such as crack tip opening displacement (CTOD) and crack tip opening angle (CTOA). Constrained by conventional test techniques and instrumentation, physical values (e.g. crack mouth opening displacement, CMOD, and CTOA angles) are measured on the test specimen exterior and a single through-thickness "average" interior value is inferred. Because of three-dimensional issues such as crack curvature, constraint variation, and material inhomogeneity, inference of average parameter values may introduce errors. The microtopography methodology described here measures and maps three-dimensional fracture surfaces. The analyses of these data provide direct extraction of the parameters of interest at any location within the specimen interior, and at any desired increment of crack opening or extension. A single test specimen can provide all necessary information for the analysis of a particular material and geometry combination.

Keywords

Microtopography, ductile fracture, three-dimensional, CTOD, CTOA, crack tunneling

Introduction

Ductile fracture processes are common to failures in a large percentage of structural materials. In many instances, a great deal of effort has been made in material development to ensure against brittle fracture in structural components. Ship steels, steel for offshore structures, pressure vessel steels, line pipe steels, and structural steels for buildings and bridges are all designed to prevent brittle fracture at ambient and operating temperatures. The physical designs of fabricated structures are usually such that there is redundancy (over-determination) built in. This redundancy allows, in most circumstances, the local loading to be distributed to other parts of the structure if a crack grows to a size causing significant local deformation. This reduces the local loading, and hopefully the crack growth arrests before complete separation of the local cross-section. In some cases, the possibility of unstable fracture does exist because structural redundancy cannot be incorporated, for example with pipelines. In these cases, the behavior and energy absorption of ductile crack growth is especially important.

Plastic deformation is stress-strain path dependent, and for practical cases where there is no reversal of stress (tension to compression, or vice versa) the deformations are permanent. These features of plasticity, including complex stress-strain distributions and non-uniform material flow associated with ductile fracture processes, make analytical modeling of the fracture process difficult. McClintock has made significant contributions with his slip line fracture mechanics methodology, e.g. in Reference 1 and others, but it is relatively new and not widely employed for analysis. It does have limitations and is sometimes difficult to apply. Because of the difficulties in developing closed form analytical solutions for ductile fracture, it is characterized with various experimentally measurable criteria. The crack tip opening displacement (CTOD) is widely applied to characterize crack initiation in the more ductile structural materials. More recently, the crack tip opening angle (CTOA) has evolved as a parameter to characterize ductile crack extension, primarily in "thin" materials with low average crack tip constraint. The crack tip opening angle (CTOA) parameter has evolved to be the most widely accepted property to characterize fully plastic fracture. The CTOA, while conceptually simplistic, does require some considerations for both measurement and design application.

In both instances, the tests used to determine the material properties (actual parameter value at the crack tip) rely on inferences from an external, or remote, measurement. For CTOD, the tip value is estimated by correcting the measured opening displacement of the crack mouth, accounting for average crack length and crack flank center of rotation (ASTM E1820-99). Figure 1 shows this measurement in graphical form. In the case of CTOA, some type of optically-based measurement of the crack opening shape is made at the outer (side, or lateral) surface of the specimen. Figure 2 demonstrates this measurement. While these methods are adequate for routine assessment, there are instances where assumptions or general unknown effects, some of which are identified in the preceding figures, may cause unacceptable inaccuracies. Some cases of present interest include plate or bar specimens where the ASTM thickness requirement (to achieve "maximum" constraint) is not met, and relatively thin sheet materials. The case of very thick specimens may also present special problems. The required assumptions force all of these methods to assume uniform two-dimensional behavior, including a single constant value of the parameter of interest at any state of crack opening or growth, as well as mandate a straight-front crack assumption. However, almost every crack front has some amount of curvature. Variations in the shape, or curvature, of the crack border require that there are variations in the opening geometry as a function of position along the border. For example, CTOA varies both as a function of early crack extension, and by through-thickness position, even in thin sheet material [2]. The relation of crack border curvature to crack opening geometry is discussed in detail in a later section. Because of these variations, a complete understanding of the behavior within the specimen interior is required before an equivalent "constant CTOA" fracture criteria can be applied. The microtopography approach presented here allows detailed study of the fracture process within the "interior" portions of the specimen.

Microtopography is a method of measuring and interpreting residual plastic deformation of fracture surfaces, such that the fracture process that created it can be re-created in a virtual sense by numerical manipulation of the spatial data. Properties of the fracture process, including crack tip opening at initiation ($CTOD_i$), crack tip opening angle (CTOA), and evolution of crack border shape (tunneling), can be determined. This particular microtopography measurement system was first applied in a study of CTOD variation around the perimeter of part-through surface cracks by Reuter et al. [3], but earlier related work was carried out by Kobayashi et al. [4]. Kobayashi's work was strictly concerned with ductile crack tip opening displacement associated with the onset of cleavage fracture, and did not address stable growing cracks or their associated characterizing parameters. Southwest Research Institute implemented their Fracture Reconstruction and Analysis (FRASTA) system [5] about the same time the Idaho National Engineering and Environmental Laboratory (INEEL) microtopography methodology was under initial development. FRASTA uses a similar measurement philosophy, but its application focuses on smaller size scales and localized behaviors. The INEEL microtopography methodology considers many significant details concerning the generalized modeling of the ductile fracture process, including unique three-dimensional interpretations of the raw surface height data over the entire fracture surface.

Theory of the Method

The fundamental principal behind the microtopography method is based on permanent deformations caused during ductile crack growth. These deformations occur during ductile crack growth that result in the creation of an increasing crack opening (CO) volume as the fracture process proceeds. The volume increases by crack extension (planar area increase) and concurrent crack surface separation. The evolution of the form of this volume is predominantly a function of crack tip processes. The two-dimensional case[a] described simplifies the description of the microtopography theory, but the principles presented can be extended directly to three-dimensional analysis without further assumptions. References to crack opening volume apply generically to three-dimensional cases, and correspond to a two-dimensional case with unit thickness.

The concept of a crack tip process zone (PZ) and its definition are important to the microtopography analysis method. Differentiating the material response within the PZ, and outside of the PZ, forms the basis of the method's capability. For this discussion, the PZ is defined as a region of the fracture surface immediately around the crack tip, as shown by the dashed line on the right side of Figure 3. Permanent deformation during the ductile fracture process originates within this PZ The process zone extent is not precisely defined in geometric terms, and depends on many factors. However, this zone will be small relative to the dominant dimensions of the specimen or structure considered in many cases. In micro-mechanistic terms, the process zone is a region of the crack tip from which dislocations emanate, hence allowing material movement, or flow, relative to the tip region. Figure 3 presents this concept in a graphical manner.

The microtopography analysis method does not attempt to directly assess actions or material response within the PZ, but rather the resultant deformations caused by those actions. The PZ, as defined, confines all significant distortional behavior that <u>creates</u> the crack opening volume and defines its physical form. The fracture surfaces created within the tip PZ do not undergo significant further shape change once they exit it. Once outside of the tip process zone, the surfaces are essentially free of normal and shear stress. For that reason, there is no driving force to cause surface distortion.[b] This reasoning applies to a large majority of specimen and crack geometries used for ductile fracture investigation. The motions of the resultant fracture surfaces are only some combination of translation and rotation in a rigid manner. This is the fundamental premise of the microtopography method – <u>once the fracture surfaces exit the near-tip process zone, they do not undergo any significant deformation with continuing crack extension.</u> Figure 4 represents this argument schematically. This

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[a] In actual practice, a physical three-dimensional space is measured, and resulting data analyzed.

[b] There are possible circumstances when these stress conditions are not satisfied, including but not limited to very short cracks, or notches with initial large face angles . High gradients in stresses tangential to the surface could lead to small distortional components, for example near the outer surface intersection point. These situations are not addressed in the analysis method described here, but have been considered.

premise of rigid translational behavior of the crack flanks behind the process zone is also supported by theory of plasticity. Immediately ahead of the crack tip is the *logarithmic spiral* flow region. The area of the crack tip bounded by the log spiral region corresponds to the process zone, PZ, described in this research. Above and below the crack tip and log spiral region are the *centered fan* regions. McClintock, in section 22.3.2 of Reference 6, states "…fan-shaped regions above and below the logarithmic spiral transmit the normal components of displacement without change from the rigid region (outside of the fan) to the boundary of the logarithmic spiral region." This is shown graphically in Figure 5 (reproduced with permission from Figure 22.4 within Reference 6). The rigid translation motion is parallel to the opening direction in all material behind the tip of, and outside the boundary of, the logarithmic spiral region as indicated by the vector components parallel to $\bar{U}$. (Note: in this reproduced figure coordinates (x,y) correspond to coordinates (y,z) within the rest of this work.) By this reasoning, the crack flank surfaces outside of the tip process zone will move parallel to the rigid motion of the surrounding elastic material. Therefore, the fracture surfaces, in their final shape, contain the entire kinematic process history that created them.

Since the entire crack process history is contained within the crack surface shape, all required physical measurements are performed entirely after the conclusion of the fracture process. The fracture process parameters are determined for any state of the fracture process using these post-test measurements. This makes microtopography a powerful tool for both ductile fracture research, and for failure analysis studies. Because it measures the physical fracture surfaces after the crack has grown, application to test specimens does not require any special instrumentation or procedures during the test – another benefit. Auxiliary measurements, such as CMOD, can be collected during a specimen test, allowing process parameters determined by microtopography to be correlated to applied force, load-line displacement, etc.

Methodology

Microtopography Data Collection

Microtopography uses the final crack opening volume as a fracture process road map. Measuring the height of the two opposing crack surfaces at the "end" state, as a function of position on the surfaces, creates this final three-dimensional opening volume map pair. The INEEL designed and constructed a data collection system using a stepper motor-driven X-Y stage assembly to move the specimen, and a laser-based, triangulation-type range sensor to measure fracture surface heights. A custom-built software application controls the system. This combination allows spatial resolution in the (x,y)-plane of about 10 µm and fracture surface height resolution of about 1 µm. Fracture surfaces with height variations over 25 mm can be measured (large specimens with slant fracture dominant). Typical scans record 20,000 to 60,000 points on 25 to 100 µm intervals over a rectangular grid. The raw data make up two data sets – the lower surface height map, $Z_l(x,y)$, and the upper surface height map, $Z_u(x,y)$. The two data sets are correlated through a common planar coordinate system, (x,y). The common reference plane (Z = constant) is selected to be approximately normal to the dominant crack opening stress direction. Figure 6 shows a representative alignment based on a symbolic middle-cracked tension-type specimen.

Alignment of Data from Opposing Fracture Surfaces

Registration (matching) of corresponding locations on the two surfaces is important to achieve accurate results. Initial alignment is accomplished during the scan set-up using two or more identifiable, corresponding macroscopic features, such as a specimen corner, on the two surfaces. A high magnification video image – 3 to 4 mm across a monitor screen – allows the operator to precisely position the fracture surface relative to the height sensor. The laser spot projected onto the surface by the sensor serves as a positional reference. An experienced operator can achieve positioning repeatability better than 25 μm. Translation and rotation of the specimen coordinate system of the second fracture surface data set brings the specified locations on the two surfaces into optimized alignment. To improve the accuracy of the analyses, fine coordinate adjustments on data subsets are sometimes made during subsequent analyses using local surface features as reference points.

Preliminary Data Processing

The physical starting point of the fracture process – the initial process state – is known, as is the ductile fracture process ending state. The initial state is that state immediately prior to the onset of the ductile fracture process. Physically, this corresponds to some region (in the case of an elastic precrack), or at least a line of crack initiation, in the (x,y) space having zero opening volume. Independent height translation and planar rotation of "upper" and "lower" fracture surface data maps can be performed to bring this region or line to a zero height difference. Following from Figure 6 and Figure 7a-7c, Figure 7d shows this relationship. At this state, a zero opening datum, $\Delta z = 0$, and the initial crack border location are established.

Figures 7e-7f depict intermediate stages of crack growth. The ending state (Figure 7g) corresponds to the physical conclusion of the ductile fracture process. This could correspond to specimen separation by tearing (as in the schematic representation of Figures 6 and 7), post-tearing fatigue cracking, or a transition from ductile to cleavage-type fracture. The data, as measured from the two crack surfaces, are representative of this final state. Relative translation in Z between the two surface maps, possibly combined with rigid rotation, will move the two data sets between these two known states. The spatial areas of the data sets defining the positive crack opening volume (hatched area in Figures 7e-7g) at any intermediate point between the two known states is representative of the physical crack opening volume at that state in the actual fracture process. The boundary of intersection of the upper and lower surface (locus of zero height difference) represents the instantaneous crack border position.

At any intermediate process state, regions of calculated negative opening volume exist when the entire data set is considered. We define these regions as "virtual material overlap," and they correspond to areas of connected material, yet to be separated by the fracture process. These areas are labeled "virtual overlap volume" (VOV) in Figure 7. Since they have no physical meaning, these regions are usually suppressed in graphical analysis of the data.

A Practical Example

From the view of microtopographic analysis, a specimen with symmetric geometry, loading, and crack position presents the simplest case. The symmetry of the middle-cracked tension specimen [ASTM M(T)-type], as presented in Figures 6 and 7, undergoes little in-plane rigid specimen rotation during crack growth.[c] In this case, analysis involves parallel separation of the two fracture surface data sets to re-create the ductile crack growth process. At selected crack opening increments, analysis of the resultant crack opening profiles determine the crack opening angle and crack extension. True CTOD, the physical separation of the initial crack tip, is assessed directly from the separation of the surfaces. Other geometric definitions of CTOD, such as the CTOD_{90} (see Reuter et al. [3]), are readily applied. Any definition of CTOA is applied in a straightforward manner offering the additional insights afforded by access to measurements in the specimen's interior. The instantaneous crack extension at a given opening increment is also available by locating the intersection of the upper and lower fracture surfaces. Figure 8 shows consecutive process states for a representative

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[c] Moderate rotations are possible if large amounts on non-symmetric crack extension occur.

crack cross-section. The solid profile line represents the "lower" fracture surface; the dashed line the "upper" surface. A thinner crack profile line weight identifies the VOV region. Five crack growth states are shown in the figure:

(0) The initial state. Precrack regions are aligned – crack is closed. Data to the right of the initial crack tip, a_0, has no significance.

(j) Crack tip blunting. Crack opening volume is increasing, tip is blunting. No material "tearing." Figure 9 depicts this stage schematically.

(i) Crack initiation. Tearing, identified by cusp formation and decreased CTOA very close to the tip, is beginning.

(t) Early tearing regime. The data in the selected example shows a large void opening just ahead of the macroscopic crack tip. Figure 10 provides a schematic representation of process zone behavior in this regime.

(f) The final state. The HSLA steel specimen was chilled in liquid nitrogen, then re-loaded until the specimen broke by cleavage fracture mode.

During this progression, some relative rotation of the data (profile lines) is applied based on instantaneous crack length, ΔCO, and estimated center of rigid rotation. Forcing alignment at the initial and final states – known conditions – allows optimization of the crack growth reconstruction.

Optimizing the Process Reconstruction

Known boundary conditions and external measurements can be applied to optimize any rotational component applied at intermediate states. The process zone actions that create the new crack surfaces cause translational separation of the surfaces outside of the process zone, creating the main component of crack opening volume. In the case of global bending, such as with a single edge notch bend specimen, the crack faces behind the PZ may also undergo rigid rotation due to non-uniform (non-symmetric) stress distributions ahead of the advancing crack tip. This rotational component creates additional crack opening volume but, importantly, does not change the shape of the crack surfaces. Applying known states in the fracture process and knowledge of kinematics of rigid motion of the specimen, the raw data (upper and lower profiles) are adjusted to include this rotational component. For common specimen geometries, such as the SE(B) or C(T), the equations that predict the position of center of rotation (ASTM Designation E 1820-99, Standard Test Method for Fracture Toughness Determination) serve as a basis for the rotational correction.

The present implementation of our analysis method applies the translational component of opening, Δz, as the independent variable (process control parameter). Δz is equivalent to the CTOD measured at the initial crack tip location. The initial process state sets Δz equal to zero as a datum. The remaining variables are dependent upon the collected height data, subject to the physical boundary conditions that must be preserved. The instantaneous average crack length, as determined at each increment of the reconstruction process, is applied in these equations to determine the center of rotation for the next opening increment. The opening increments, $d(\Delta z)$, are kept small, usually 10 to 20 µm, so the corresponding crack extension increments are small. Additional correction factors are applied to the center of rotation calculation so that the known physical boundary conditions are not violated.

Characterizing Two Regimes of Ductile Crack Growth

Ductile fracture process behavior can be categorized into two regimes: initial tip blunting and subsequent material tearing. In the blunting regime, material flow is localized to the vicinity of the crack tip. Material flows on curved paths that begin at the crack tip, but intersect the crack flanks in close proximity to the tip. The result is a smoothly curved profile (on the appropriate size scale) characteristic of the initial crack tip blunting. Incremental crack extension is approximately equal to crack opening on the same increment, resulting in a smoothly curved tip opening profile. Figure 9 shows this relationship. At some point in the process, a transition occurs and material flow starts to exit the local tip region. As shown in Figure 10, the majority of material flow (dislocation motion) is now away from the tip, commonly localized in particular directions – slip line directions. The angular, sometimes jagged, crack opening profile is characteristic of this regime of "ductile tearing." There is an abrupt change in the local crack opening profile shape at initiation, and microtopography can readily identify it, along with the corresponding local CTOD.

Once tearing initiates, ductile fracture surfaces tend to be macroscopically rough (on some size scale), and the crack advance path tends to meander above and below the nominal growth plane in a somewhat random manner. McClintock has characterized the local tip process associated with this tearing regime by an incremental "sliding off" of material along the slip directions, leading to meso-scale crack opening and crack advance. Figure 11 is a schematic depiction of several consecutive increments in the process. As shown, this process results in crack face separation behind the advancing crack tip. Microtopography measures these local perturbations with micron height resolution and 10 µm resolution in (x,y) position. Because the mating surface height data correlate with this accuracy, microtopography is capable of characterizing localized surface roughness. It also offers the possibility of localized micron-scale CTOA measurements – something that is impossible with optical surface measurement methods.

Assessing Instantaneous Crack Front Profiles (Tunneling)

The assessment of crack border shape and tunneling is of interest in several areas of fracture mechanics research. In many cases, significant crack tunneling can occur leading to poor estimates of crack extension and inaccurate (by some methods) estimates of the instantaneous CTOA and corresponding "true" crack length. This is a difficulty particularly associated with optical surface measurements of crack length and CTOA. CTOA measurements are now being incorporated in finite element models, and these experimental measurement errors have potential to adversely effect the model results. As these crack growth modeling efforts continue to grow in the three-dimensional regime, correct crack front shape evolution is critical for accurate model results. Microtopography offers an efficient and accurate method to determine these crack front shape evolutions. Applying knowledge of the kinematic behavior that creates the ductile fracture surfaces, microtopography analysis can extract the evolution of crack front curvature (tunneling) during growth. Analyzing and mapping the calculated fracture surface separation distance does this, using the following rationale and approach.

Recall the fundamental premise of the microtopography method: once the fracture surfaces exit the near-tip process zone, they are essentially stress free (normal and shear stress near zero) and do not undergo any significant deformation with continuing crack extension. This premise mandates that fracture surfaces outside of the tip process zone do not change shape, but only translate, and possibly rotate, in a rigid manner. In cases of moderate to long cracks in typical through-cracked plate, single-edge-notch bend, and compact tension specimens, this is a reasonable presumption that was justified in the section on Theory of the Method. Various experiments on all of these specimen types confirm the premise, including comparisons with metallographic sections of replicate test specimens (Reuter and Lloyd [3]).

When considering the case of crack tunneling, a common misconception is that the fracture surfaces must be bowing in the Z-direction behind the crack tip, thereby allowing the crack front to change its shape in the nominal fracture plane (X-Y).[d] It is true that a section view of an X-Z plane through the fracture surfaces behind the tip of a tunneling crack will be curved. However, the curvature is not created by deformation of the surfaces after the crack has passed that location, but by the geometry and local material response (CTOA) of the growing crack. Crack tunneling during ductile growth occurs precisely because CTOA varies as a function of through-thickness position along the crack front.[e] This allows interpretation of fracture surface height difference maps as incremental crack front positions.

Stated differently, the locus of points of equal fracture surface separation describes the crack border at some state of crack growth. At any point in the process of incremental opening and corresponding growth, crack extension may vary across the crack front – more where CTOA is lower (the central thickness), less where CTOA is higher (near surface). Incremental crack border locations therefore can be derived by analyzing the separation distance between the fracture surfaces as a function of position in the X-Y plane (the nominal crack plane). A surface height difference iso-line map corresponds to positions of the instantaneous crack border, and the iso-line values can be correlated to the crack opening displacement, or vice versa.

Experiments by Lloyd and Piascik [2] (using microtopography) and Sutton et al. [4] (using replicate specimen examination) show CTOA variation with crack extension both at the surface and in the specimen interior, and the corresponding change in crack tunneling. Microtopography analysis of crack front shape showed severe tunneling at early stages of crack growth, followed by a gradual straightening of the crack front at larger crack extensions. Replicate specimen tests, interrupted at various amounts of crack extension, independently confirmed the microtopography analysis. The companion CTOA analysis of the specimen interior by microtopography showed an initially low CTOA that gradually increased to a near-steady state value of a bit over five degrees. Surface observation showed an initially high CTOA that decreased to a near-steady state value of about 4.7 deg. Assessment of the results at that time suggested that the values were the same within experimental accuracy. However, the interior “steady-state” value appeared slightly higher. This relationship of surface and central thickness CTOA with increasing crack opening would precisely correspond to the initial severe tunneling, followed by a gradually straightening crack border at larger crack extensions. This is also consistent with higher central constraint during early growth when the fracture surface was mostly flat. The transition to slant fracture, beginning at the surfaces and progressing inward to the center of the plate thickness with continuing crack extension, could be expected to cause a decrease in constraint at mid-thickness. This could explain the measured increase in CTOA along the centerline as crack length increased.

Applications

Microtopography is applicable in a number of different areas of ductile crack growth assessment. In each case, the methodology offers improvements in the level of detail available compared to alternative measurement methods, surface measurement of CTOA being one. The microtopography

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[d] This perception may be due to a mental simplification of the complex, changing geometry of the fracture surfaces and curved crack front boundary. Crack front curvature on an idealized X-Y plane is mentally translated to curvature in an X-Z plane at some instant of the fracture process, even though the crack border does not correspond to that plane.

[e] The CTOA at a given position through the thickness (X position) may also vary as a function of increasing crack growth due to material hardening or specimen geometry changes. However, those variables do not effect the argument concerning basic tunneling behavior and fracture surface curvature being discussed here.

method can obtain results from a single specimen, e.g. interior CTOA as a function of ? a, which requires analysis/investigation of multiple replicate specimens using other techniques, such as metallographic sectioning.

Early work used the microtopography methodology to assess the variation of the initiation value of crack tip opening displacement in ductile surface crack specimens. The alternative was metallographic sectioning of replicate test specimens that had loading halted at different points. Examination of many metallographic cross-sections from the different specimens, and interpolation was required to make the estimates of applied stress and location of the first point of initiation, and subsequent initiation stress for other points around the crack perimeter. Microtopography offered several significant benefits over the sectioning method. Replicate crack shapes in part-through surface cracked plate specimens are difficult to achieve and each individual specimen is expensive to produce. Microtopography only requires one specimen to achieve the same result with more detail. Metallographic sectioning is very time-consuming and it destroys the specimen in the process. Microtopography leaves the specimen halves intact for further study. Examination of replicate specimens by sectioning offered the original confirmation that the microtopography technique was providing valid results (Reuter et al. [3]).

The crack tip opening angle is receiving increased interest as a parameter to characterize the ductile fracture process in low constraint geometries. Thin plate/sheet material used in the aerospace industry is a good example. Microtopography was used to investigate the CTOA variation in the interior of 2.3 mm thick aluminum alloy M(T) specimens (Lloyd and Piascik [2]). In this case, the data were unavailable by other means, and the data collected from the specimen surfaces were suspect because of the tunneling observed in replicate specimen tests. The microtopography analysis showed substantially different evolution of CTOA at the specimen mid-plane than at the surface. Microtopography also correctly mapped the very substantial crack tunneling behavior observed in later replicate specimen tests performed at another site. This work served to validate the microtopography capability to derive incremental crack border shapes using only a single specimen tested to large amounts of crack extension.

Another area of increased interest is the ductile fracture process in weldments. The nonhomogeneous nature – microstructure, fracture toughness, yield strength – of the material near welds is a cause for concern when conventional measurement techniques are applied. Microtopography is being applied in the study of ductile fracture in various weldments at INEEL. One aspect that is currently being investigated is the effect of highly irregular crack border shapes and irregular crack tunneling on the values of CTOD assessed using conventional "two-dimensional" test methods. The ASTM Round Robin Test Program for Fracture Toughness Testing of Weldments [5] discusses some of these problems. Microtopography analysis has good potential to provide increased understanding of the ductile fracture process in both homogeneous materials and weldments through better use of conventional test results.

Summary

The microtopography method provides a range of new capabilities in the analysis of the ductile fracture process. Microtopography provides the capability to find the initiation value of the CTOD, and location along the crack border where initiation occurs. The subsequent evolution of crack front shape can be derived for small to large amounts of crack growth from only a single specimen. The CTOA of the growing crack can be determined at any location along the crack border, from the surface through the specimen interior at any stage of the fracture process, again using only a single specimen. Microtopography allows all aspects of the deformation caused by the ductile fracture process to be thoroughly investigated and characterized. Conventional ductile fracture parameters can be extracted from the resulting data. In some cases, such as with the initiation CTOD, it is a direct measurement from the graphical data. In other cases, like with the CTOA, the values are readily derived from the raw data using any of several descriptions of that parameter. The microtopography methodology allows investigation of the ductile fracture process in ways that are not possible by any other means, providing new insights to advance knowledge in this vitally important area of fracture mechanics.

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Figures

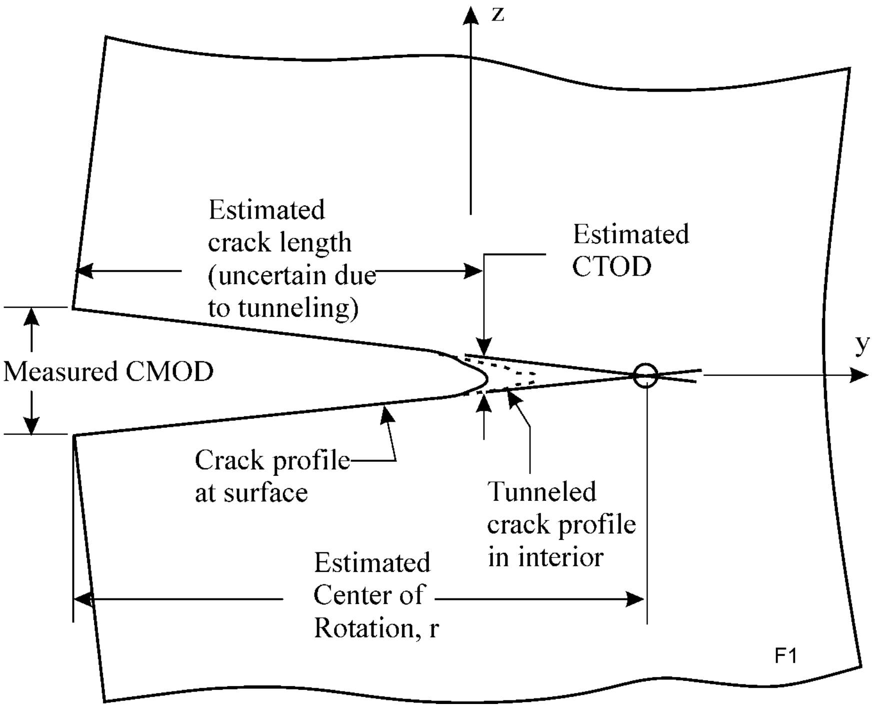


Figure 1. Two-dimensional crack representation and related parameters.

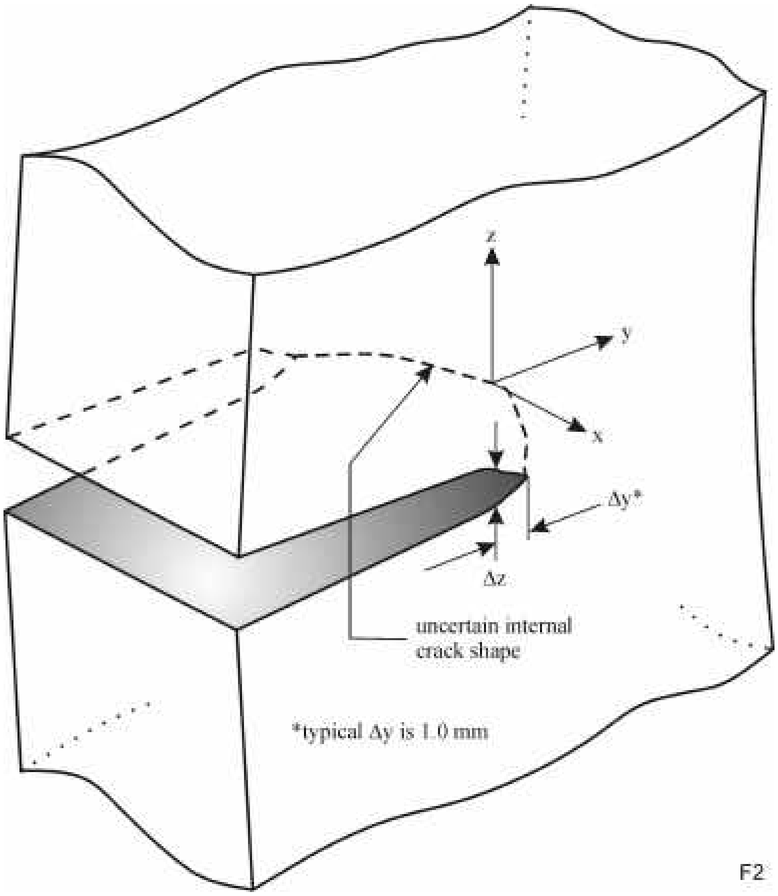


Figure 2. Three-dimensional characteristics of a "two-dimensional" test specimen. Internal crack shape variation, and external surface CTOA measurement shown.

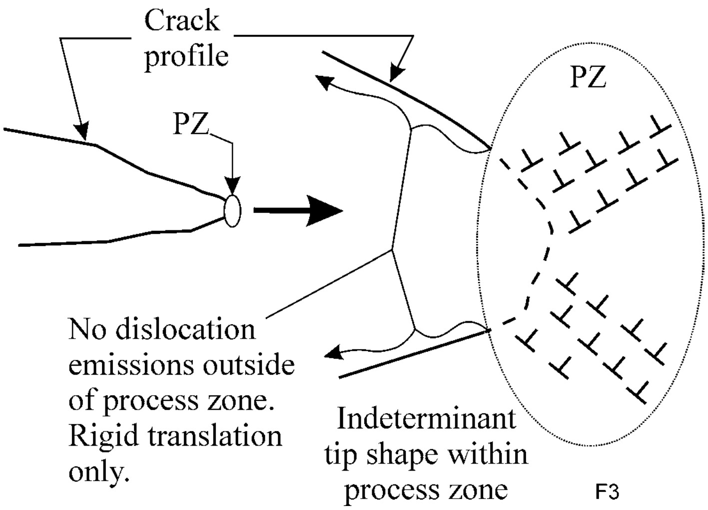


Figure 3. Schematic representation of a crack.tip profile and fracture process zone (PZ). Dislocation emission within the PZ leads to resultant fracture surface shape behind the process zone as the fracture process proceeds.

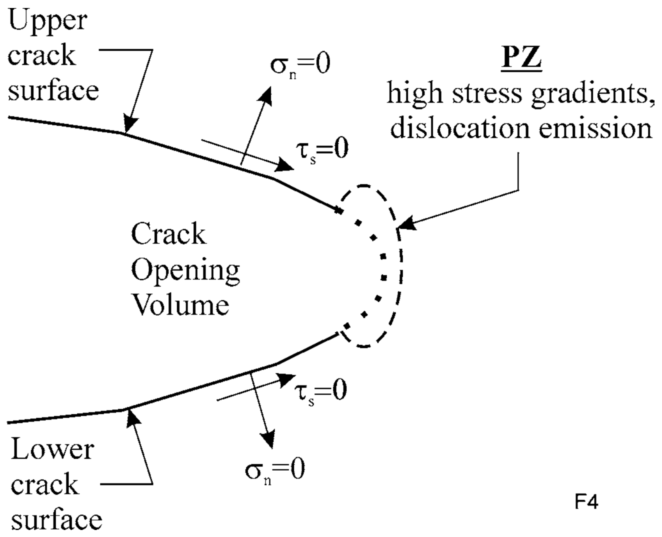
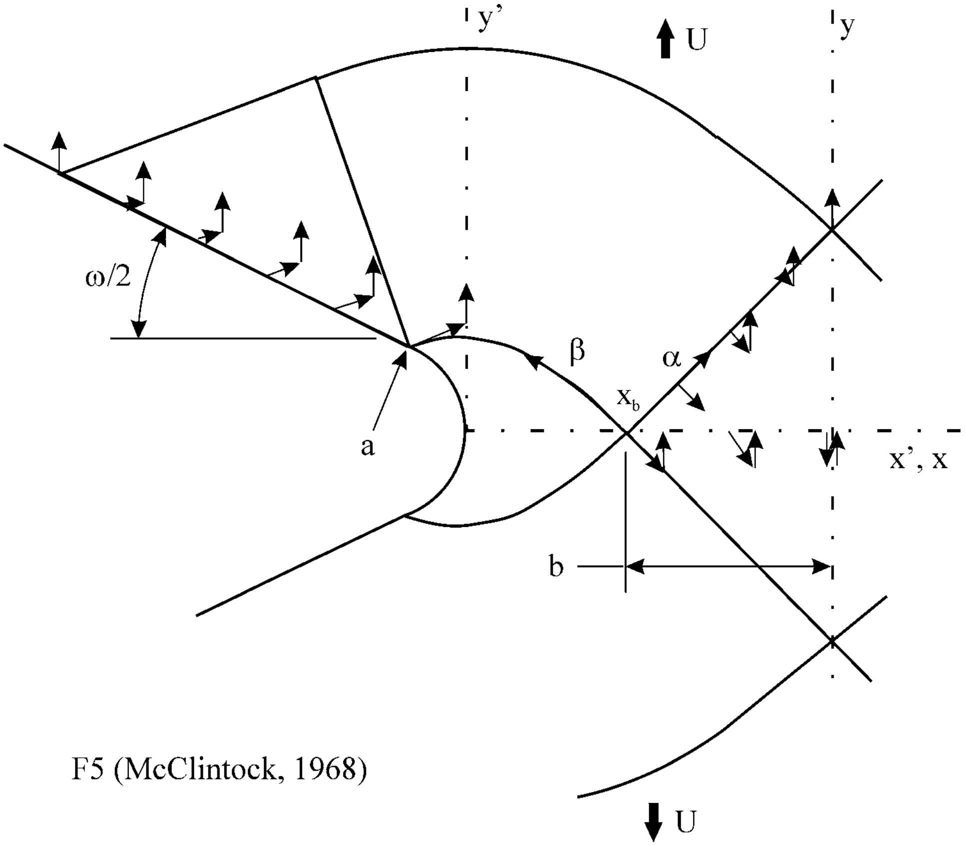
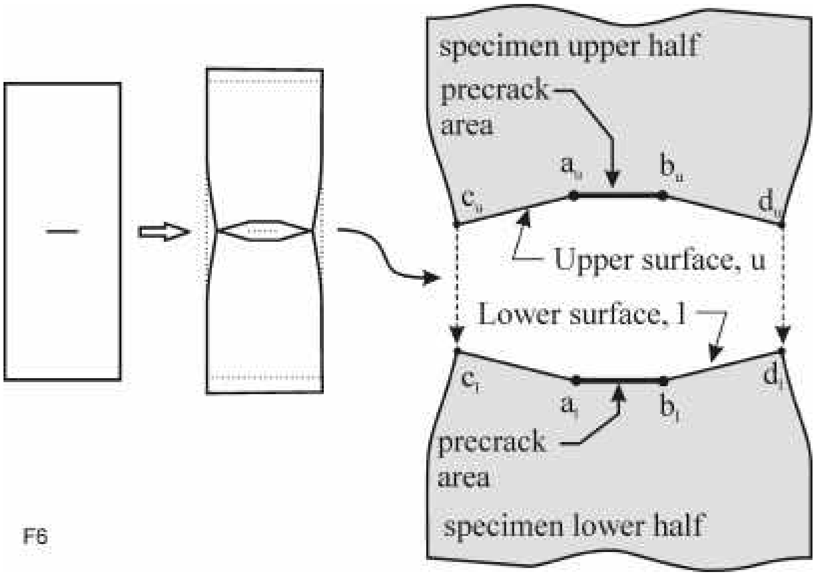


Figure 4. Crack tip profile, showing essentially traction-free surfaces behind the process zone.



F5 (McClintock, 1968)

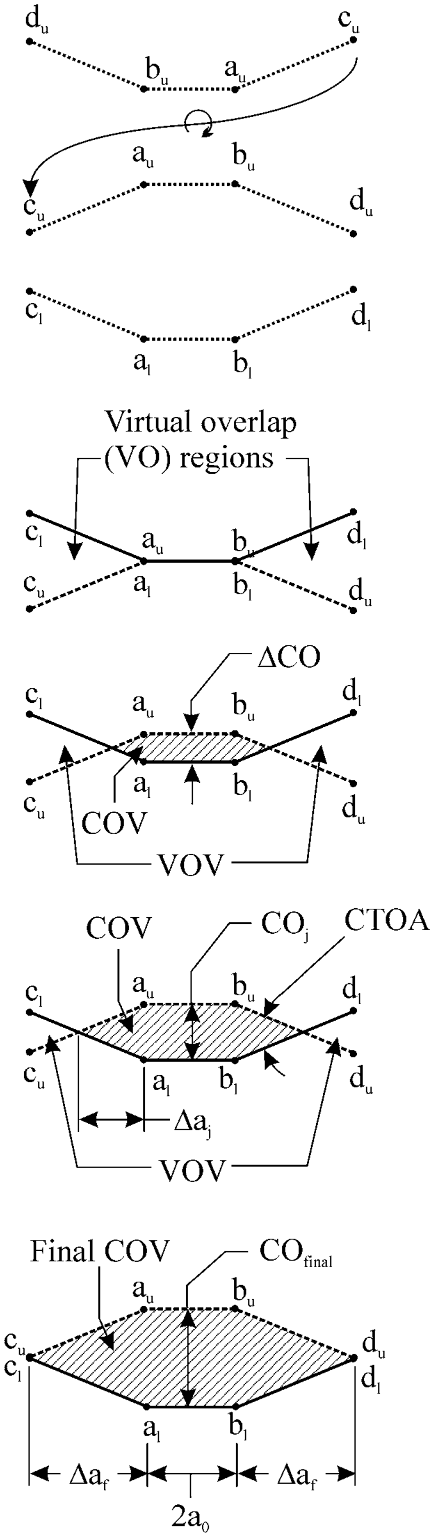
Figure 5. Plastic flow around a blunted notch tip, from non-hardening plasticity theory (adapted with permission from Figure 22.4 in Physics of Strength and Plasticity [6]). The logarithmic spiral region at the notch tip corresponds to the process zone discussed elsewhere in this article.



F6

Figure 6. Idealized fracture process of a middle cracked tension [M(T)] specimen shown schematically, with corresponding points on the two fracture surfaces indicated.

Representative profiles (Y-Z sections) of idealized M(T) specimen



(a) Upper surface profile, as digitized, $-Z_u(-x,y)$.

(b) Upper surface, inverted & mirrored to correlate to lower surface positions, $Z_u(x,y)$.

(c) Lower surface profile, as digitized (no changes), $Z_l(x,y)$.

(d) Surface data sets (lower - solid, upper - dashed) adjusted to align precrack area (ab), $(Z_u - Z_l)_{ab} \approx 0$.

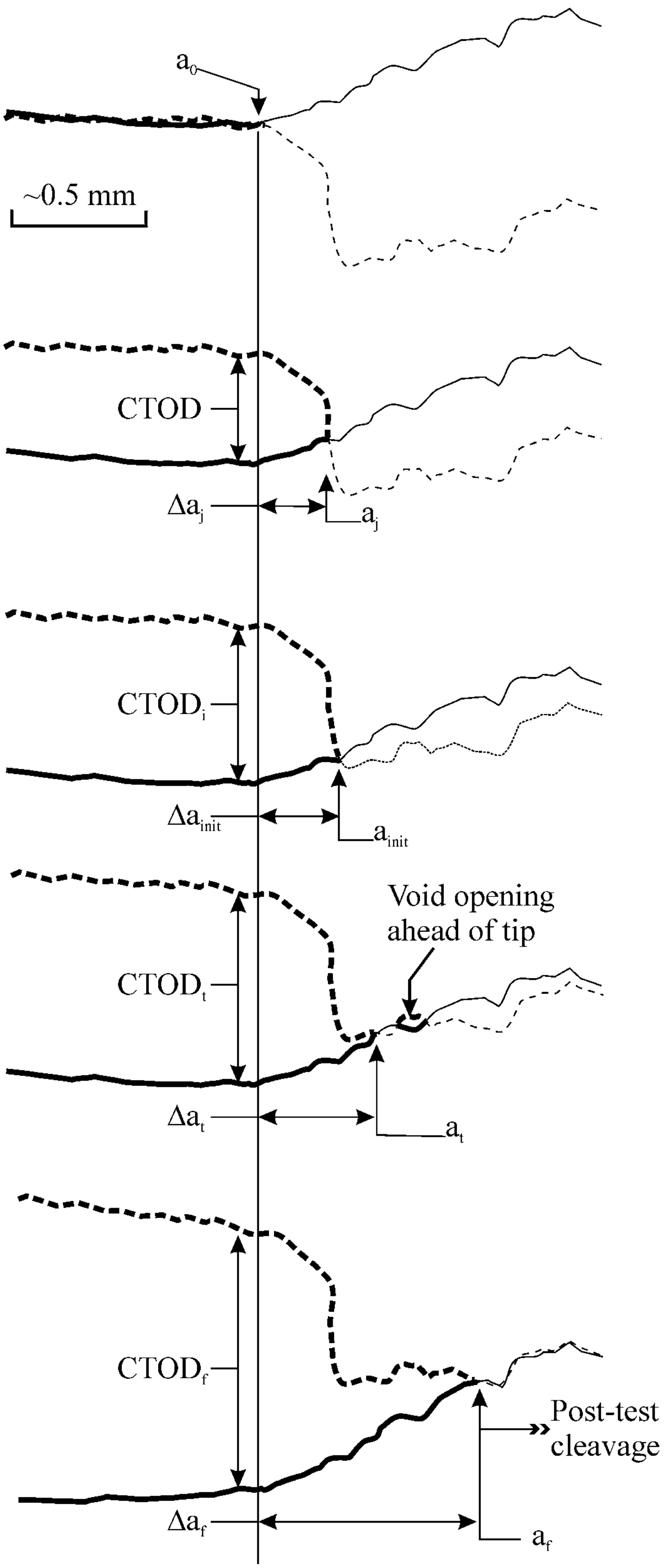
(e) Crack opening increment, ΔCO, applied. Crack opening volume (COV) created, virtual overlap volume (VOV) reduced. Crack extends by $\Delta a = \Delta CO/2*\tan(CTOA/2)$.

(f) Data representation after additional opening increments. CTOA remains constant in this example.

(g) Crack profile data positioned at final state. Last points of material separation coincide.

F7

Figure 7. Graphical fracture process analysis of the data from idealized M(T) specimen shown in Figure 6. Features, regions of interest, and characterizing parameters are shown.



Analysis of real crack profile data (HSLA steel). Solid line = lower surface contour. Dashed line = upper surface contour.

Data where lower surface contour is above upper surface contour (light lines) do not have physical significance.

Crack extension analysis progresses from top to bottom. Crack tip opening increments between subsequent analysis states. Relative contour rotation is applied based on instantaneous crack length such that final state (f) aligns.

(0) Initial state, precrack surface area aligned (superimposed). Data points to right of a0 have no significance.

(j) Tip still blunting. No tearing. Tip profile still approximately semi-circular.

(i) Crack initiation. Tearing just beginning.

(t) Crack tearing. Crack has advanced from initiation point. Note area ahead of tip where void is appearing in the material.

(f) End of tearing. Specimen was chilled and broken by cleavage. Cleavage fracture (elastic) surfaces superimpose since no plastic deformation associated with crack extension.

F8

Figure 8. Graphical fracture process analysis of data (one internal crack profile shown) from an HSLA steel SE(B) test specimen. Features commonly observed in microtopography analysis are identified.

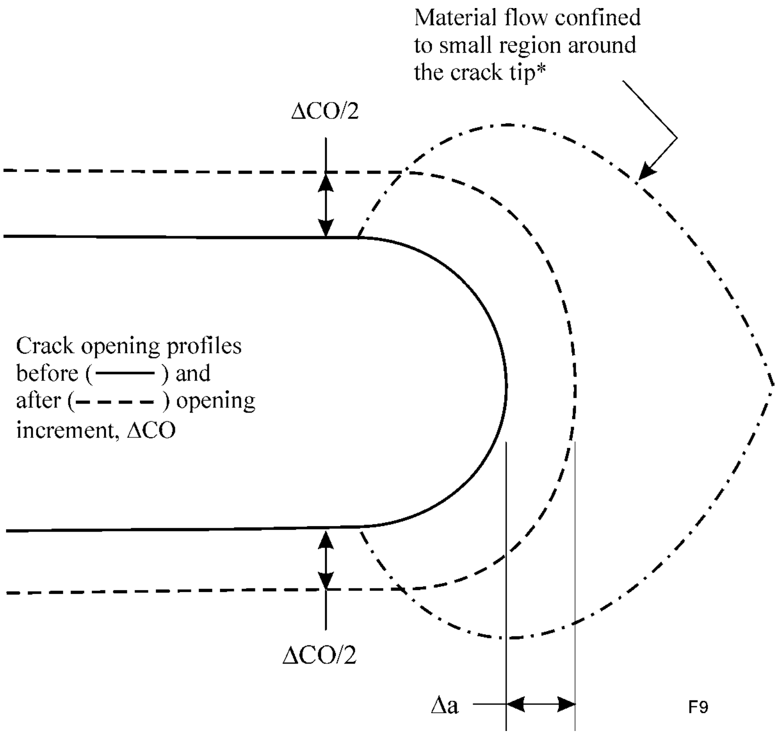
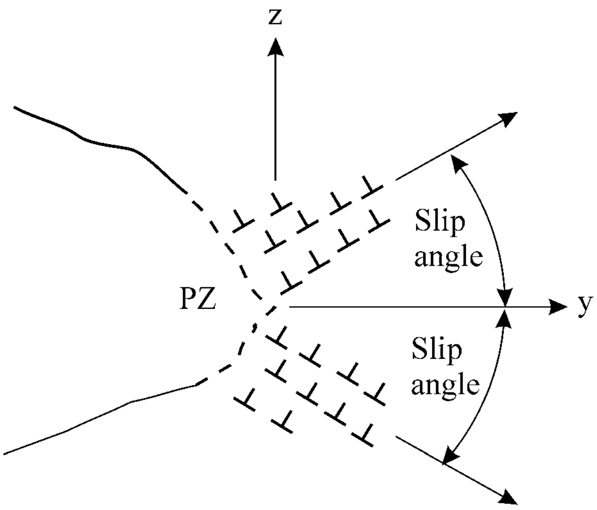


Figure 9. Idealized crack tip shape showing change corresponding to one increment of CTOD, ΔCO, during the tip blunting regime of the ductile fracture process.



F10

Figure 10. Schematic representation of crack tip region during the tearing regime of the ductile fracture process. Details of plastic flow within the process zone are not represented.

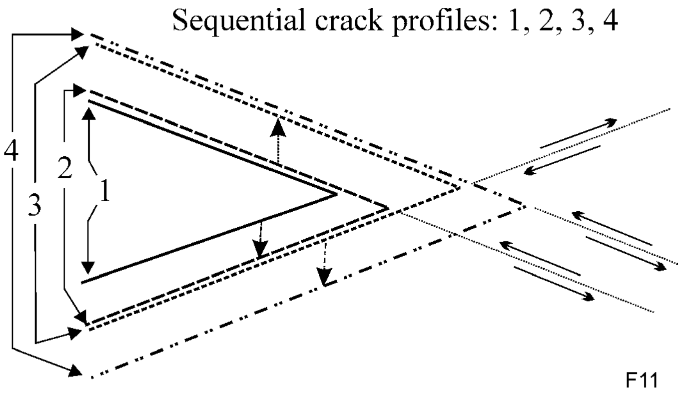


Figure 11. Schematic representation of idealized crack tip region, showing progress of crack opening and extension during alternating material slip along two dominant slip bands. Although this shows uniform, discrete increments, the actual process is continuous and irregular, leading to the rough fracture surfaces characteristic of ductile tearing.