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A Relationship Between Constraint and the Critical Crack Tip Opening Angle

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ABSTRACT

Of the various approaches used to model and predict fracture, the Crack Tip Opening Angle (CTOA) fracture criterion has been successfully used for a wide range of two-dimensional thin-sheet and thin-plate applications. As thicker structure is considered, modeling the full three-dimensional fracture process will become essential. This paper investigates relationships between the local CTOA evaluated along a three-dimensional crack front and the corresponding local constraint. Previously reported tunneling crack front shapes were measured during fracture by pausing each test and fatigue cycling the specimens to mark the crack surface. Finite element analyses were run to model the tunneling shape during fracture, with the analysis loading conditions duplicating those tests. The results show an inverse relationship between the critical fracture value and constraint which is valid both before maximum load and after maximum load.

1. INTRODUCTION

Ductile fracture is a three-dimensional process in metals. Constraint (stress triaxiality) varies along a crack front, from higher constraint at the crack mid-point to lower constraint at the crack surface. Many early analyses [1] of sheet and thin plate metallic materials used some form of a two-dimensional approximation, but it was found that neither plane stress nor plane strain conditions adequately captured both the local near-tip high constraint and the far-field low constraint. More recent analyses [2] used three-dimensional models that restricted the through-thickness crack front shape to be straight. As thicker structure is considered, modeling the full three-dimensional fracture process will become essential.

Of the various approaches available to model and predict fracture, the Crack Tip Opening Angle (CTOA) fracture criterion has been successfully used for a wide range of applications. In particular, for sheet and plate materials, CTOA has been used successfully in predicting the residual strength for complex built-up structures involving load redistribution as well as complex integral structures involving crack branching [3]. Three-dimensional models, with a straight crack front, adequately capture the constraint variations while ignoring the three-dimensional nature of the local fracture process. It has been hypothesized [4] that this simplified three-dimensional approach works well with a single value for CTOA because the single value represents an average fracture criterion that is controlled by an average deformation state, and thus an average constraint state near the crack front.

The objective of this paper is to investigate relationships between the local CTOA evaluated along a three-dimensional crack front and the corresponding local constraint for a thin-plate aluminum alloy. Tunneling crack front shapes were measured previously [5, 6] during fracture by pausing each test and fatigue cycling the specimens. Finite element analyses were run to model the tunneling shape during fracture with the analysis loading conditions duplicating these previous tests. Thus, the analysis was run in a generation mode to approximate the deformation and stress state for the test and to determine the relationships between the fracture criterion and constraint.

2. BACKGROUND

Wells [7] originally proposed the use of the Crack-Tip-Opening Displacement (CTOD) or angle (CTOA) during his experimental work. Investigations at NASA Langley Research Center [8] incorporated the CTOA criterion into Finite Element Analysis (FEA) codes and developed CTOA into a viable fracture criterion for thin-sheet aerospace industry applications. A number of researchers have applied CTOA or the related CTOD in various industries [3]. The CTOA criterion is applied in this work as the angle formed by stable tearing material measured at a fixed distance, d = 1 mm, behind the moving crack, and the criterion assumes that the critical CTOA, Ψ_c, is constant and independent of loading and in-plane configuration, as long as the crack length is about 4 times the plate thickness [4].

Dawicke, et al., [9] and more recently Mahmoud and Lease [10], measured CTOA on the surface of either compact tension, C(T), or middle-crack tension, M(T), specimens and found that, except for an initial transient in the angle where tunneling was developing, the angle was constant with crack growth and was essentially the same for the two specimen types. These results strongly indicate that the CTOA fracture criterion is constant for large amounts of crack growth both before maximum load and after maximum load. Dawicke, et al., [11] found similar results using three-dimensional finite element analysis. Lloyd and Piascik [12] also found similar results measuring the angle in the interior in experiments using micro topographic methods. More recently, James and Newman [2] performed a variety of fracture tests to characterize the fracture behavior of 6.35 mm thick 2024-T351 aluminum alloy plate. Approximately half the specimens failed with a flat fracture surface. Follow-on studies [5, 6] focused on establishing crack length measurement methods when tunneling is present.

3 ANALYSIS PROCEDURE

This section describes how the previous experimental tunneling results [5, 6] in the background section were used in the present analysis to characterize the deformation and constraint states. The current study uses the measured load and flat fracture tunneling data of the previous studies as input to analyses performed. Figures 1 and 2 summarize these previous results. To characterize tunneling, the crack was grown under displacement control to a predetermined length on individual specimens. Cyclic loading was then applied at a high load ratio (R = 0.75 or 0.8) and high maximum load (80% of the current fracture load) to fatigue mark the stable tearing crack front shape. Typically, about 2000 cycles were applied to mark the crack front. After the specimens (thickness, B=6.35mm) were broken open, the crack front shapes were measured using an optical microscope with X-Y traveling stages. Figure 1 shows results from a typical fracture surface after a test, including the measured fatigue pre-crack shape and the tunneling fracture crack shape. The symbols correspond to known crack front locations, and the lines correspond to the final tunneled crack front shape. The average surface crack length, Δa_s, was calculated as the average of the crack length on both surfaces. The tunneling magnitude, T, was calculated as the maximum crack length value minus the average surface crack length. Figure 2 shows load versus average surface crack growth data for two tests (open symbols) from reference [2], and the figure shows crack tunneling data from references [5, 6]. Each of the tunneled crack data tests is represented by a horizontal pair of filled symbols. The filled circles represent the average crack length (Δa_s) from a test, and the filled triangles represent the tunneled maximum (Δa_s+T). The surfaces crack length measurements from the tunneled tests (filled circles) agrees well with the surface crack measurements from the original tests (open symbols). Starting at the second pair of tunneled data, the data shows clearly that the crack length in the interior of the specimen rapidly transitions to a tunneling crack that is significantly longer in the interior than the length on the surface. By the third data set of tunneled crack fronts, the tunneled maximum (Δa_s+T) is up to 2.5 mm while the surface crack length (Δa_s) is less than 1mm.

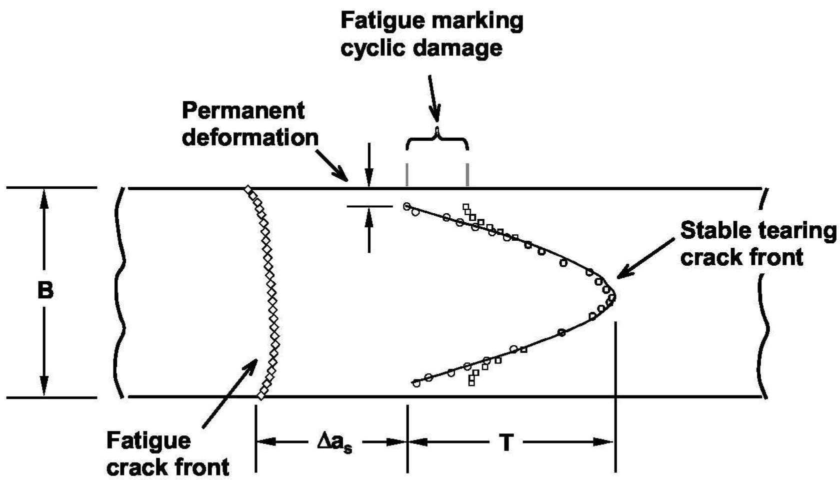

Figure 1: Tunneling experiments, fractured to specified crack length, then fatigue cycled to mark the crack-front shape (drawing to scale).

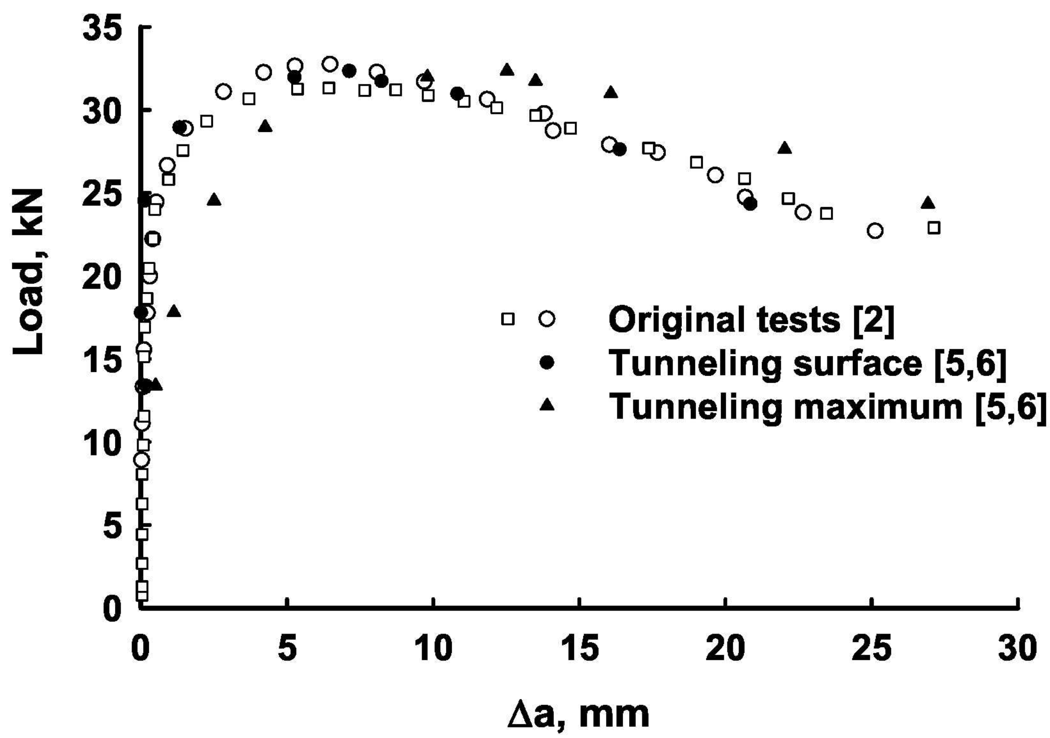

Figure 2: Comparison of previous surface measured crack growth with tunneling surface and interior measurements.

3.1. Material And Specimen Configuration

The data in Figure 2 were reduced to provide tunneling amplitude (T) as shown in Figure 1. These results were used to describe the tunneling behavior for the FEA procedure. A through-thickness sine wave-form approximated the crack-front shape. For the analysis, the symmetry was assumed through the thickness. The tunneling magnitude increased from the initial fatigue crack-front until it stabilized at Δa_s = 19 mm. The crack growth increment on the surface is kept constant at Δa_s = 0.25 mm. This is the same level of mesh refinement used by Dawicke [11] and is two to four times the refinement typically used for CTOA analyses [2, 10, 13].

The elastic-plastic finite element code used in this study was WARP3D [13, 14]. A multi-linear representation of the engineering (small strain) uniaxial stress strain curve with the von Mises yield criterion was used in the analysis. Because the experimental configuration was fully constrained with guide plates during test, two planes of symmetry were used to model only 1/4 of the specimen: half of the thickness and along the fracture surface. The C(T) mesh used ten eight-node brick elements through the half-thickness.

3.2. Crack Growth Procedures

In traditional fracture mechanics applications, the fracture criterion is evaluated normal to the crack front. In addition, the local fracture criterion is a function of the local stress and deformation state. Figure 3 is a schematic indicating locations where the angle and local stresses are evaluated for this work. The arrows represent the direction CTOA was measured and the dots represent the location where the local constraint was evaluated. Figure 3(a) shows the approach taken by Dawicke, et. al., [11] to characterize the material. The local angle along the crack front was measured in planes parallel to the model side-surfaces, which is the overall growth direction. Figure 3(b) shows the approach taken for the current work. The angle is evaluated normal to the crack front at points behind the crack front, and the local stress is evaluated inside the mesh in front of the crack front in the same plane in which the crack angle was evaluated.

Crack growth was modeled in WARP3D using a nodal-release technique [13]. The CTOA fracture criterion was evaluated at d = 1 mm behind the crack front along arrow tipped lines shown in Figure 3. The crack advances by simultaneously releasing the constraints for each node along the crack front. Crack-face forces on the new surface nodes are relaxed slowly over several load steps using a relaxation algorithm. The mesh has a topologically straight crack front, so the algorithms in WARP3D could be used without modification.

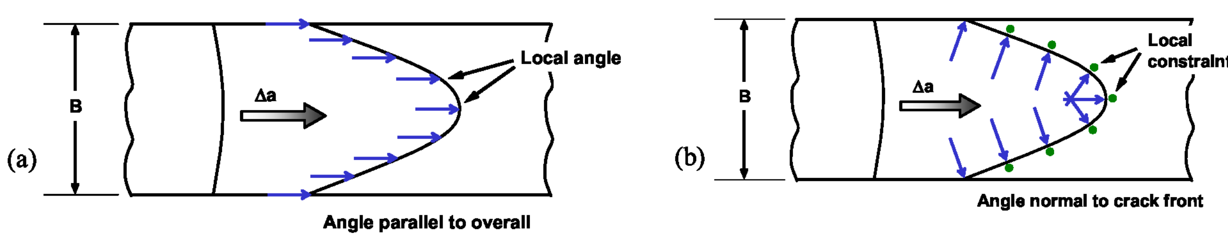

Figure 3: Schematic comparing two different ways to evaluate the local angle along a crack front.

4 RESULTS

Figure 4 is a plot of the critical CTOA with the angle measured in planes normal to the moving crack-front. The angle along the crack front monotonically increases from the center line to the surface for a given amount of surface crack growth. The angle is essentially constant at any point along the crack-front after the first 2.5 mm of crack growth, and the angle is constant well before maximum load.

The analysis results for the first four crack-growth increments ($\Delta a_s \leq 1$ mm) are likely not representative of the deformation state in the test specimen because the analysis crack front shape does not match that of the tests since growth started in the interior before surface growth occurred. This is a limitation related to the approach used to generate the finite element mesh. The primary focus of this analysis is the results ranging from just before maximum load through just after maximum load, but the other results are included for completeness. By $\Delta a_s = 1$ mm, the mesh in this study is an adequate approximation to the measured tunnelling shape.

Figure 5 is a plot of the critical CTOA as a function of the local constraint, where constraint is represented as the ratio of mean (hydrostatic) stress (σ_m) to von Mises effective stress (σ_e). The open symbols are for crack growth less than 1 mm. These results show a consistent relationship between the local deformation and the local stress state. The dashed line is a linear best-fit of the results with growth of 1 mm and greater. This relationship is valid both before maximum load and after maximum load which occurs between 2.5 and 6.4 mm of crack growth.

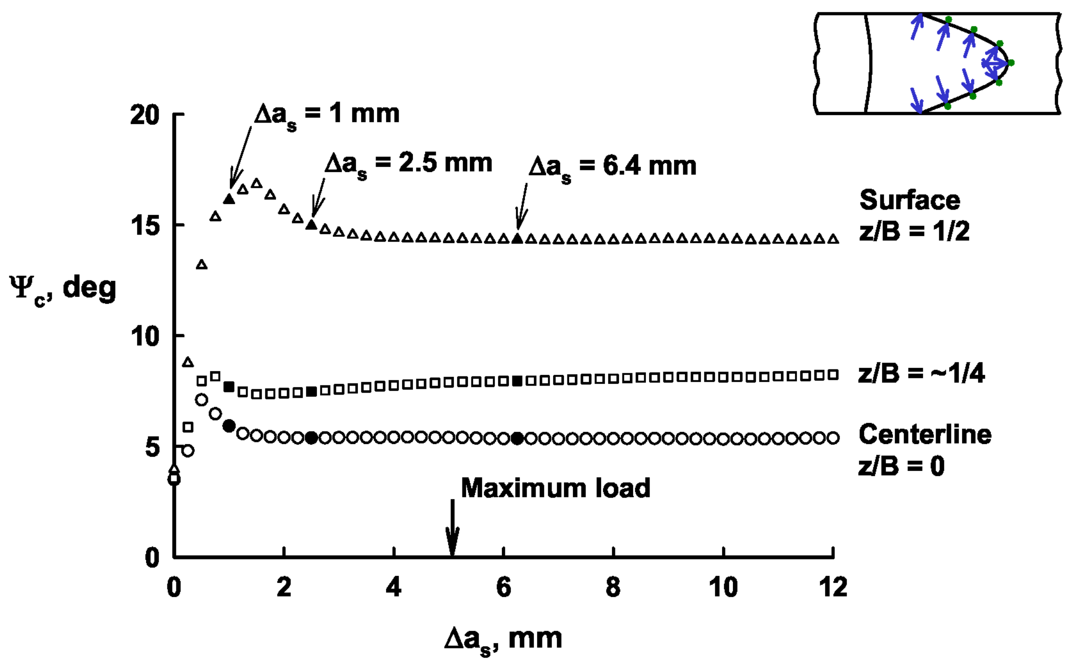

Figure 4: Surface and interior angle as a function of crack growth – method of current study (normal to the crack front).

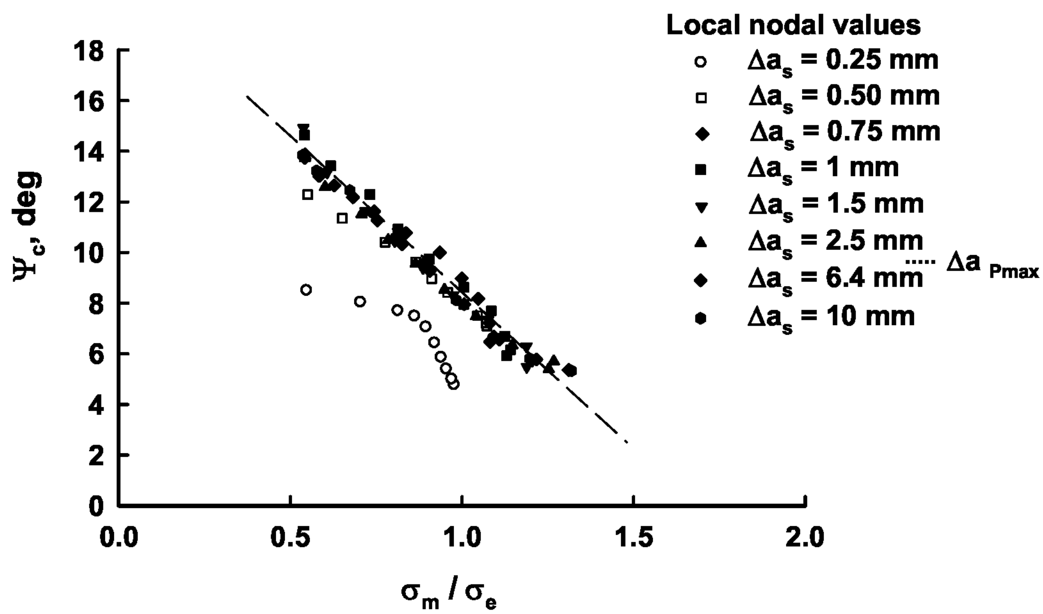

Figure 5: Local angle evaluated normal to the crack front as a factor of constraint.

5. SUMMARY

This paper uses experimental data and computational methods to investigate the relationship between a displacement-based fracture criterion and the local stress state for a three-dimensional crack that displayed flat fracture. The input to the analysis was the experimentally measured crack-front shape and load. The analysis was then run in a generation mode to interrogate relationships between deformation and the stress state.

The results in this paper confirm that the elastic-plastic fracture is dependent on the constraint state of the material in front of the crack. The analysis results on the surface of the model are consistent with previous experimental and analytical studies. The analysis results in the interior were interpreted using local stresses near and displacements normal to the curved crack front. The results show that the local angle along the crack-front is a linear function of constraint (expressed as the ratio of mean stress to effective stress). This relationship may prove useful for establishing a predictive fracture model that accounts for local deformations and local constraint.

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14. ABSTRACT
Of the various approaches used to model and predict fracture, the Crack Tip Opening Angle (CTOA) fracture criterion has been successfully used for a wide range of two-dimensional thin-sheet and thin-plate applications. As thicker structure is considered, modeling the full three-dimensional fracture process will become essential. This paper investigates relationships between the local CTOA evaluated along a three-dimensional crack front and the corresponding local constraint. Previously reported tunneling crack front shapes were measured during fracture by pausing each test and fatigue cycling the specimens to mark the crack surface. Finite element analyses were run to model the tunneling shape during fracture, with the analysis loading conditions duplicating those tests. The results show an inverse relationship between the critical fracture value and constraint which is valid both before maximum load and after maximum load.

15. SUBJECT TERMS
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