The Effect of Thickness on the Characterization of Crack Tip Opening Angle for 2024-T351 Aluminum Alloy

Samer Mahmoud and Kevin Lease

Department of Mechanical and Nuclear Engineering, Kansas State University,
Manhattan, KS 66506, USA

ABSTRACT

The crack tip opening angle (CTOA) parameter has been shown to be well suited for modeling stable crack growth and instability during the elastic-plastic fracture process. Furthermore, this parameter, implemented in both 2D and 3D elastic-plastic FEM codes, has been successfully applied to stable tearing and stability analyses of some very complex structural configurations made of thin-sheet 2024-T3 aluminum alloy. However, the effect of material thickness on the characterization of this parameter has not been thoroughly evaluated. Therefore, an investigation was conducted to assess the effect of material thickness on the characterization of the CTOA parameter for 2024-T351 aluminum alloy. Stable tearing fracture tests were conducted on C(T) specimens in four thicknesses (2.28, 6.35, 12.7, and 25.4 mm), with all specimens taken from a single 25.4 mm thick plate. Overall, the average experimental surface critical CTOA (ψ_C) values obtained from the current work were found to decrease with increasing specimen thickness. The amount of crack extension necessary for the transition to a fairly constant CTOA value was not characterized by the specimen thickness for the three largest thicknesses tested in this research, as observed in the earlier thin-sheet tests. As the specimen thickness increased, discrepancies between the experimental (surface) CTOA values and those obtained computationally were shown to increase. More thorough experimental and computational investigations into the effects of surface vs. interior CTOA values and/or crack tunneling must be performed before CTOA characterization can be directly applied to thicker specimens.

KEYWORDS

fracture-experimental, fracture-computational, stable crack growth, crack-tip opening angle

INTRODUCTION

One of the most promising parameters that have been introduced to simulate the elastic-plastic stable tearing process is the crack tip opening angle (CTOA) defined at a specified distance (d) from the crack tip. Numerous investigators [1-6] have characterized and evaluated (both experimentally and computationally) the CTOA parameter and have found that it is nearly constant after a small amount of crack extension. The non-constant CTOA region (measured at the free surface) has been shown [1,2] to be associated with severe crack tunneling during the initiation of stable tearing. These characterization results have also been utilized in numerous finite element-based fracture analyses to simulate the stable tearing and stability of both simple and complex structures with excellent results [2-5]. The majority of these CTOA characterization and analysis studies have focused on aluminum alloys in thin-sheet form in support of the aerospace industry's damage tolerant and aging-aircraft efforts. This paper describes an experimental/computational investigation into thickness effects on the characterization of the crack tip opening angle (CTOA) fracture parameter in 2024-T351 Aluminum. The experimental portion of the current project consisted of conducting stable tearing fracture tests using C(T) specimens of various thicknesses. These tests provided measurements of CTOA and crack extension on the surface of the specimen as well as load and load line displacement history through out the stable tearing process. The computational portion of this work involved three-dimensional finite element based CTOA fracture analyses to simulate the stable tearing process in the test specimens. These analyses were used iteratively to obtain the mid-thickness critical CTOA (ψ_C) value that produced the closest agreement between the predicted maximum applied load and the experimentally measured values.

MATERIAL, SPECIMEN, AND EXPERIMENTAL PROCEDURES

The 2024-T351 Aluminum alloy was chosen for this study in order to allow for the direct comparison to, and extension of, the previous CTOA characterization work on thin-sheet (1.0, 1.6, 2.3 mm thickness) form of the 2024-T3 alloy [6]. The thickness range chosen for this research included 2.3, 6.35, 12.7, and 25.4 mm. The 2.3 mm thickness was chosen to correspond to the thickest specimens evaluated in the previous thin-sheet 2024-T3 work. Compact tension (C(T)) specimens (W = 203 mm) with a chevron starter notch were used for all fracture testing in this study. All specimens were machined out of a single 25.4 mm thick plate of 2024-T351 in the L-T orientation. Uniaxial tensile tests were conducted (in the L-T orientation) to determine the monotonic stress-strain properties for the acquired 2024-T351 plate. The test set up for all stable tearing fracture tests consisted of a material testing machine, clevis grips, a microscope, a CCD camera, a VCR, and computer hardware/software for controlling the machine and facilitating the image acquisition. Anti-buckling guide plates were used with the 2.3 mm and he 6.35 mm thick specimens. All specimens were pre-cracked to provide an initial crack length to specimen width ratio of 0.4 using an R = 0.1 sinusoidal loading and keeping K_{max} below 13 $MPa\sqrt{m}$. The actual stable tearing fracture tests consisted of an incremental displacement controlled ramp waveform (rate = 0.002 mm/sec) that would pull the specimen apart until a stable tearing event was detected visually. At this point, the test was temporarily paused to record load, load line displacement, and VCR counter, and to reposition the microscope as needed to track the crack tip. After manual data logging, the ramp test was resumed until another crack growth increment was observed, repeating this process until complete specimen fracture occurred. Along with the video-taped history of the surface cracking behavior, automated logging of load and load line displacement was obtained by the testing machine internal data acquisition system.

A commercial digital image analysis software package with integrated length and angle measurement tools was used to measure CTOA and crack extension for each stable tearing event. To perform a single CTOA measurement, a series of frames ranging from just prior to just after the onset of stable tearing were transformed from the VCR tapes into an image sequence file. The image sequence file was then played at a slow speed and the frame containing the image showing the specimen surface at the onset of a tearing event was selected for measuring the CTOA. As outlined by Dawicke *et al.* [1], CTOA measurements were made at a distance behind the crack tip ranging between 0.25-1.0 mm. Six to ten angle measurements were made and the average of the measurements was selected as the representative critical CTOA (ψ_C) for that particular crack length. By once again reviewing the image sequence file, the image corresponding to the end of the current stable tearing event was then determined. Using the crack tip location from the previously selected image and the final crack tip location the crack extension was measured, using the length measurement tools, and recorded for each stable tearing event.

COMPUTATIONAL PROCEDURE

The computational phase of this project involved three-dimensional finite element based CTOA fracture analyses to simulate the stable tearing process in the test specimens. By modifying the input critical CTOA (ψ_C) value, these analyses were used iteratively to determine the mid-thickness critical CTOA (ψ_C) value that produced the closest agreement between the predicted maximum applied load and the average experimentally measured values. The three-dimensional elastic-plastic finite element-based fracture analyses were performed using the ZIP3D program [7]. A discretized, multi-linear representation of the tensile stress-strain curve obtained for the 2024-T351 plate was used to incorporate the material properties into the simulation. To implement the critical CTOA (ψ_C) fracture criterion, ZIP3D calculates the CTOD/CTOA value at the first central free node behind the current crack tip (1 mm behind the current crack tip). When the CTOA value at this node reaches the specified critical value, ZIP3D releases the next set of tied nodes. It should be noted that the critical CTOA (ψ_C) value input to ZIP3D specifies the critical CTOA (ψ_C) at the center of the specimen, whereas the experimentally measured CTOA behavior corresponds to the specimen surface. However, the CTOA values for all crack front nodes across the specimen thickness can also be obtained from the ZIP3D output, facilitating at least a partial comparison of measured and calculated surface CTOA values. The 3D mesh of the C(T) specimen used in this study was generated by extruding a 2D mesh in the thickness direction to produce five layers of eight-noded isoparametric elements, producing a total of 13662 nodes and 10790 elements. The elements at the crack face were 1 mm long. Only one fourth of the 203 mm C(T) specimen was modeled due to symmetry about the crack plane and the mid-thickness of the specimen.

RESULTS

Figure 1 shows the experimentally measured surface CTOA versus crack extension behavior for all four thicknesses of the 2024-T351 alloy evaluated in this study. As can be seen, all four specimen thicknesses exhibited similar behavior with the CTOA starting at a high value followed by a rather rapid decrease to a fairly constant value after a small amount of crack extension. In Figure 1(a) (2.3 mm thickness) experimental data from the earlier thin-sheet 2024-T3 work is also included for comparison purposes. As can be seen, this data compares quite closely to the data obtained in the current work for this thickness. The scatter in Figure 1 was generally within ±1.5 degree and the amount of scattering appears to decrease with increasing specimen thickness. Also, the amount of crack extension necessary to transition to a fairly constant CTOA value is seen to decrease with increasing specimen thickness. This is in contrast to the observation in the earlier thin-sheet 2024-T3 work [1, 2] that this transition crack extension was characterized roughly by the specimen thickness. The horizontal solid line in each plot in Figure 1 represents the numerical average of the data points in the constant (or “critical” CTOA) region. The dashed vertical line, designated as “Max Load” in each plot, indicates the amount of crack extension where the maximum fracture load occurred.

Figure 2 provides a comparison between the experimental and calculated critical CTOA (ψ_C) values for all four thicknesses of the 2024-T351 alloy evaluated in this study. Also shown in this figure are the calculated results from the earlier 2024-T3 thin-sheet study (1.0, 1.6, and 2.3 mm thickness) [6]. As can be seen from this figure, the experimentally determined surface critical CTOA (ψ_C) value for the 2.3 mm thickness compares quite closely to the computational result from the earlier thin-sheet study for this thickness. Furthermore, the overall trend of the critical CTOA (ψ_C) value decreasing with increasing specimen thickness that was shown in the earlier thin-sheet study was also shown in the results of the current work. The experimentally determined surface critical CTOA (ψ_C) values from the current study appear to imply that a lower limiting value of surface critical CTOA (ψ_C) may exist for this alloy. For the thicknesses evaluated in this study, two sets of calculated CTOA values are shown in Figure 2. The first set corresponds to the ZIP3D center node (mid-thickness) values. These correspond to the actual ZIP3D input values that produced the closest correlation between the calculated and experimental maximum fracture loads. The second set of calculated CTOA values in this figure correspond to the ZIP3D surface CTOA value at the moment that the center node (mid-thickness) value reached the input critical value. As can be seen, the experimentally determined surface critical CTOA (ψ_C) values fall between the mid-thickness and surface CTOA values calculated from ZIP3D for each thickness. Moreover, the difference between the interior and exterior CTOA value increases with increasing specimen thickness. While the calculated surface values in this figure show a decreasing trend that mirrors that of the experimentally determined surface CTOA values, the calculated mid-thickness CTOA values do not show a definite trend. It should be noted that the CTOA computed at the surface of the specimen is for a stationary (non-tearing) straight (non-tunneling) crack front.

Figure 3 compares the measured and computed load vs. crack extension curves for all four thicknesses of the 2024-T351 alloy evaluated in this study. It should be noted that the computational curves shown in this figure were obtained from the ZIP3D analyses with the critical input mid-thickness CTOA (ψ_C) value (solid diamonds in Figure 2) that produced the best correlation between the measured and calculated maximum fracture loads. For all four thicknesses it can be seen that the predicted curve either matches or slightly under-predicts the experimental behavior prior to the maximum load and then either matches or over-predicts the experimental behavior after the maximum load. As indicated in Figure 3(a), scattering of the experimental data for the 6.35 mm thick specimens occurred due to the fact that one of the specimens had a slightly longer initial crack length (a/w=0.416) while another specimen exhibited a change in crack growth orientation from across to along the grain after a short amount of stable crack extension.

CONCLUSIONS

Thickness effects on the characterization of the CTOA parameter were investigated using 203 mm C(T) specimens fabricated from 2024-T351 Aluminum alloy in the L(T) orientation. The experimental results obtained in this study for the 2.3 mm thickness compared quite closely to the published values [1, 2, 6] for this thickness. Experimental results also show that the amount of crack extension necessary for the transition from an initially high CTOA to a fairly constant critical value decreases with increasing specimen thickness and overall the critical CTOA (ψ_C) value decreases with increasing thickness. The experimentally determined surface critical CTOA values fall between the mid-thickness and surface CTOA values calculated from ZIP3D for each thickness. Moreover, the difference between the interior and exterior CTOA value increases with increasing specimen thickness. More thorough experimental and computational investigations into the effects of surface vs. interior CTOA values and/or crack tunneling must be performed before CTOA characterization can be directly applied to thicker specimens.

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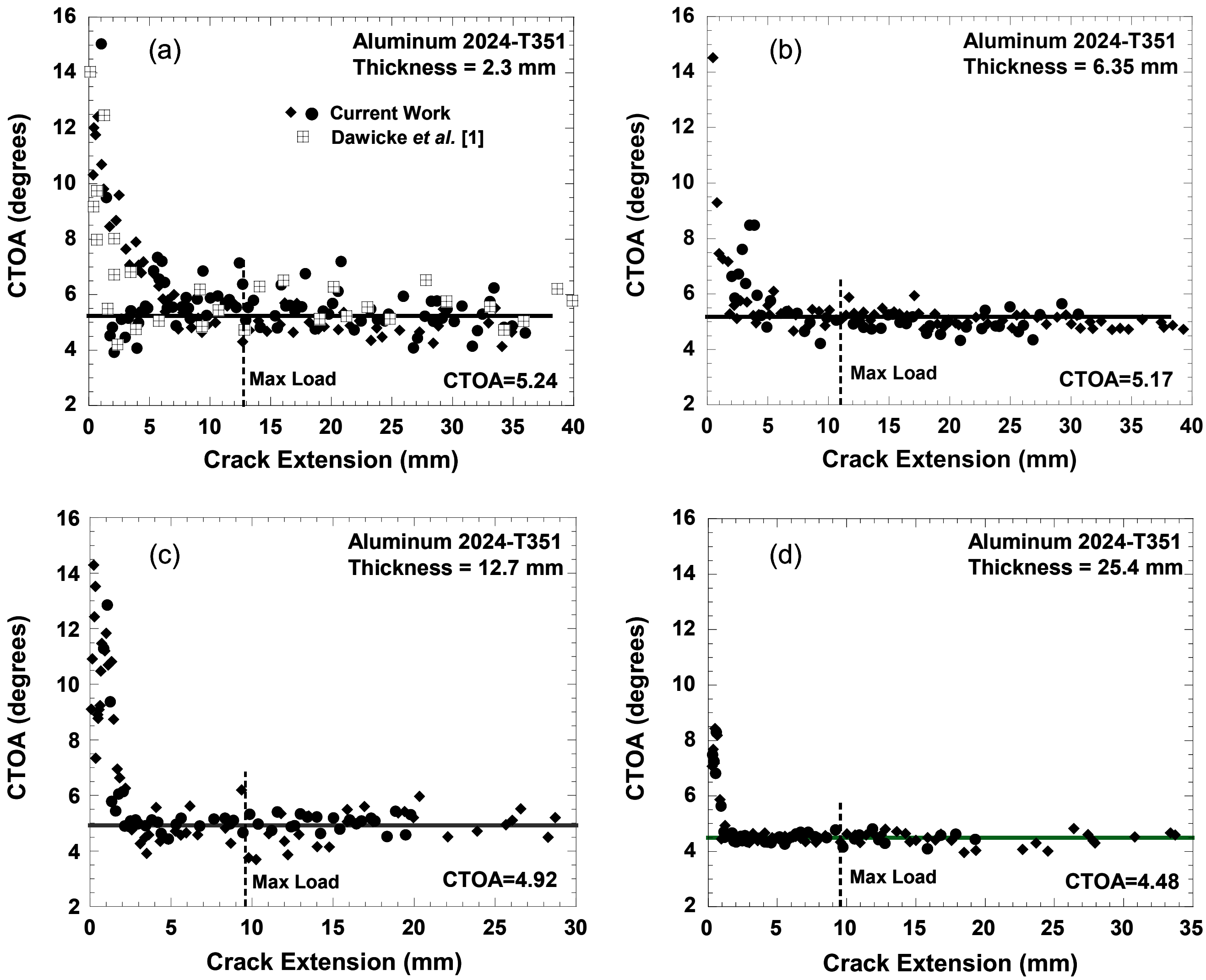

Figure 1: Experimental surface CTOA versus crack extension behavior for all four thicknesses of the 2024-T351 (L-T) Aluminum alloy evaluated. (a) 2.3 mm (b) 6.35 mm (c) 12.7 mm (d) 25.4 mm

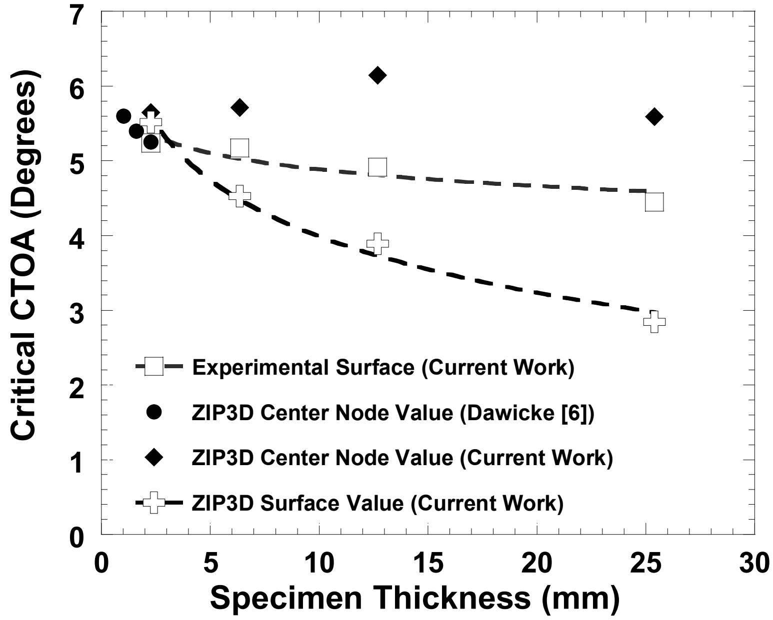

Figure 2: Experimental and computational (ZIP3D) critical CTOA values as a function of specimen thickness for the 2024-T351 (L-T) Aluminum alloy.

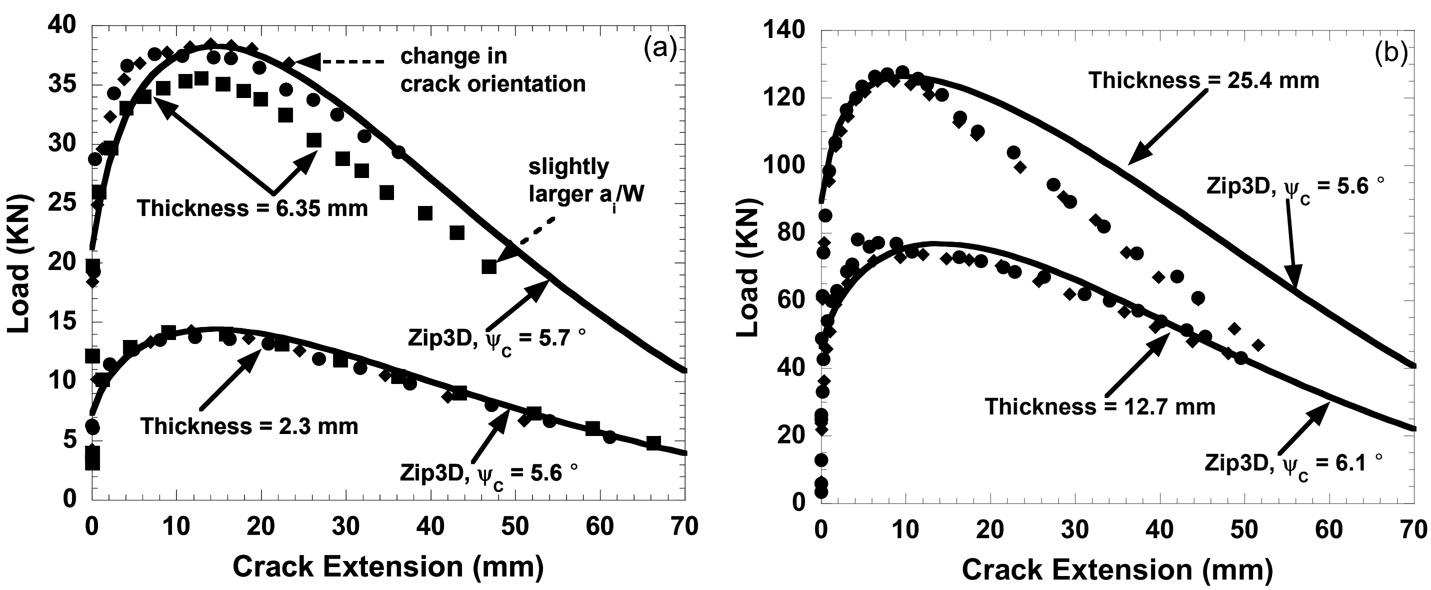

Figure 3: Experimental (symbols) and ZIP3D computational (solid lines) load versus crack extension behavior for all four thicknesses of the 2024-T351 (L-T) Aluminum alloy evaluated. (a) 2.3 and 6.35 mm (b) 12.7 and 25.4 mm