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Experimental Study of Stable Crack Growth in Thin Aluminium Sheet

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Recent failure information from research teams in NASA Langley and others has shown that CTOA based fracture models calibrated on large C(T) and M(T) specimens can be transferred successfully to cracked aircraft fuselage structures for the assessment of their residual strength. A major difficulty that could limit the more extensive use of this failure parameter is its experimental measurement either in the real structure or in a laboratory scale test. This paper describes the use of a DCB-like specimen for direct measurement of critical CTOA data for thin sheet 2024-T3 aluminium alloy used in aeronautical applications. It outlines the features of ductile crack growth in thin walled structures, the specimen design geometry for reproducing these features in a laboratory scale experiment, the experimental set up and loading configuration for tear test specimens, and the CTOA measurement scheme. Using the test technique developed, the CTOA resistance curves for test samples of 2.3mm ligament thickness were generated for fractures propagating in the rolling and transverse direction of the original rolled plate. The results of this research showed that the technique was capable of producing large amounts of highly consistent CTOA data even from one single specimen. This is promising as it provides a precise and relatively easy experimental method for direct evaluation of CTOA toughness levels of test materials using small-scale laboratory specimens. A comparison of the test results from the current work with similar data from the literature concludes the paper.

INTRODUCTION

Ductile fracture is a major failure mechanism in most engineering materials and structures. It has been shown that it occurs over three stages; crack initiation, stable growth and instable propagation. In high-strength tough materials, large amounts of stable crack extension might occur before the point of fracture instability. Different failure criteria have been proposed over the past decades to characterise the material tearing resistance in the case of large plastic deformation. Among these, CTOA has been shown to have the promise to be used for assessing the ductile fracture toughness of materials [1-5]. The CTOA fracture criterion is related to the critical crack-tip opening displacement (CTOD) concept proposed by Wells [6]. This criterion assumes that stable crack growth occurs when an angle formed by a point on the upper surface of a crack (at a fixed distance behind the crack-tip), the crack-tip itself, and a point on the lower surface (again at a fixed distance behind the crack-tip), reaches a critical angle CTOA_c, see Figure 1.

CTAO can be directly measured from the crack opening profile, related to the geometry of the fracturing structure, and implemented easily in finite element models of the propagating fracture process. Extensive study of CTOA properties of aerospace materials [7-12], gas pipeline steels [13-15], and high pressure vessel steels [16] have revealed that CTOA can be regarded as a material constant over the stable crack propagation phase. Its use as an additional or an alternative to the existing toughness assessment models of aeronautical structures is currently under review.

Comprehensive research [7-12,17-23] on the CTOA profile of spacecraft aluminium alloys of grade 2024-T3 has been conducted at NASA (National Aeronautics and Space Administration) Langley by Newman, Dawicke and their co-workers, and also by other

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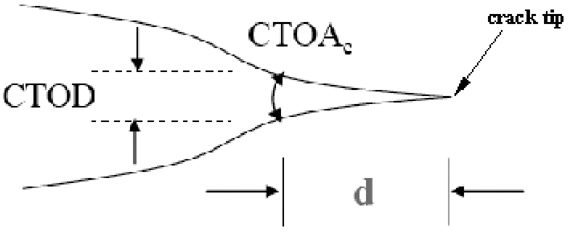

Figure 1. Definition of Crack Tip Opening Displacement (CTOD) and Crack Tip Opening Angle (CTOA) at fixed distance d (mm) behind the crack tip.

researchers. Dawicke et. al. used large dimension thin and thick compact tension C(T) and middle crack M(T) specimens of varying thicknesses ranging from 1 to 25.4mm (tested at low strain rates). Optical techniques were used to monitor the progression of the crack tip, see Figure 2.

The crack tip was located from the captured images, the crack length measurements performed and the CTOA values evaluated at a fixed distance behind the crack tip. Equation (1) then was used to calculate CTOA data during crack growth:

$$CTOA = 2\tan^{-1}(\frac{CTOD}{2d}) \qquad (1)$$

To remove the dependency of measured CTOA values on the distance d, CTOA is usually estimated for 10 points over a distance of 0.5 to 1.5 mm behind the crack tip and its mean value is used as the representative of material critical CTOA:

$$CTOA = \sum_{i=1}^{N} CTOA_i/N \qquad (2)$$

Where the $CTOA_i$ is the point value and N is the total number of measured values. The measured stable CTOA data was between 5.6^o to 4.5^o for the minimum and maximum specimen thicknesses, respectively. This indicated a minor thickness dependency of CTOA values of the order of 1^o over 25mm thickness range for aluminium alloy. Using the steady state values of CTOA in 2D and 3D finite element analyses, the residual strengths of the tested specimens were accurately estimated from the CTOA-based fracture models. The CTOA results obtained by this technique (and by digital image correlation) for Al 2024 specimens with C(T) geometry (having 2.3mm ligament thickness) are shown in Figure 3.

The main difficulty in this approach is identifying the precise location of the crack tip and two auxiliary points on the upper and lower crack edges for surface CTOA calculations. An irregular fracture edges and a curved crack front are characteristic of ductile tearing, which make the measurement of CTOA values somewhat problematic and can introduce a scatter band of $\pm 1^o$ in the obtained results.

The details of an alternative δ_5 technique for CTOA measurement on a 3mm thick A15083 H321 aluminium alloy and the comparison of the obtained data with the results from optical imaging can be found in reference [3]. The technique is able to produce steady state CTOA data with less scatter than optical systems. It is applicable for low strain rate experiments and requires the use of a special clip-gauge (see Figure 4) for Crack Mouth Opening Displacement (CMOD) measurement. Some numerical calculations are needed to derive the CTOA values from the slope of CMOD plot versus Δa.

The technique discussed in the current research for direct measurement of the CTOA data in a laboratory scale test has the following features:

- it provides large amounts of highly consistent CTOA data even in one experiment and therefore can be regarded as a single specimen CTOA test.
- the stable CTOA values can be estimated from both sides of the specimen.
- from the extensive data set the statistics on the scatter of measured CTOA values can be calculated.

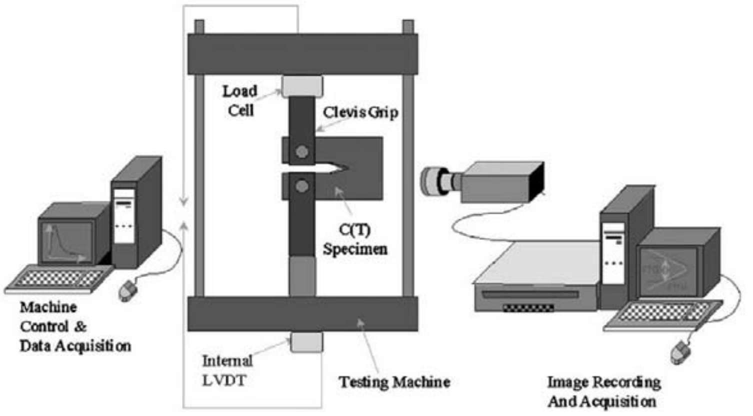

Figure 2. Schematic of experimental set up used in C(T) testing of aluminium alloy [24].

- it measures the CTOA from a rotated mesh, and hence removes the uncertainty in locating the crack tip and identifying the curved crack profile in similar CTOA estimating approaches.
- as the reference mesh is available from the very onset of the crack initiation, the CTOA data can be generated from the beginning of the test whereas some crack growth is needed for CTOA estimation from crack edges.

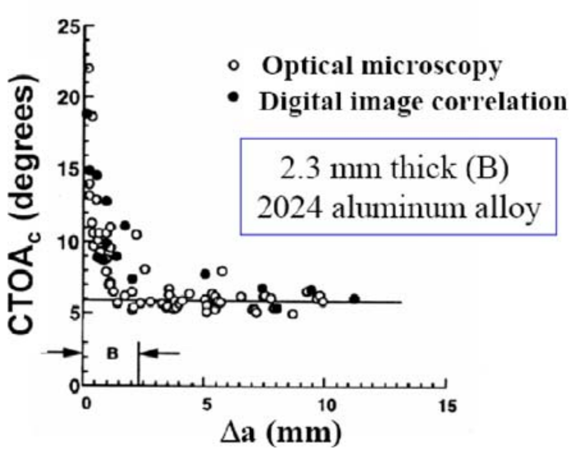

Figure 3. Variation of CTOA as a function of crack growth for 2.3 mm thick C(T) specimens made from Al 2024 [7].

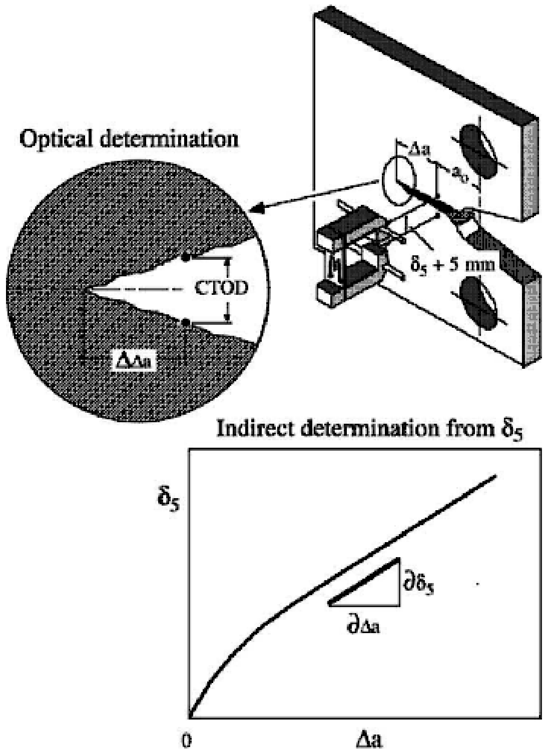

Figure 4. Basic arrangement for δ_5 technique and CTOA measurement scheme. The details of the special clip-gauge for Crack Mouth Opening Displacement (CMOD) measurement is shown in the right photograph [3].

The combination of the specimen features and the CTOA monitoring scheme make it possible to measure the CTOA data accurately for different test materials. The results previously obtained (at Sheffield University by the author and his co-workers) for pipeline steels of grade X80 and X100 have been reported elsewhere [25-27]. Recently, the author has been able to make similar test set up for CTOA testing of API X70 pipeline steel (used in Iranian main pipelines) at The University of Birjand. This was conducted in an independent research supported by Sadid Pipe and Equipment Company [28,29]. This set up has been used recently for CTOA testing of 2024-T3 aluminium alloy [30], and the obtained results are given here with a comparison of new test data with similar information from the literature.

MATERIAL PROPERTIES

The material under investigation was an aluminium alloy of grade 2024-T3 in the form of rolled plates. Its mechanical properties were measured in the axial and transverse directions using flat tensile specimens, with 5 mm gauge thickness, as shown in Figure 5.

The measured mechanical properties of test material are shown in Figure 6 and given in Table 1.

CTOA'S EXPERIMENTAL SET UP

A modified double cantilever beam (DCB) specimen was used to conduct the fracture tests. Two CTOA specimens were taken from a plate (400mm length, 200mm width and 5mm thick), one in the T-L and the other in L-T direction, where T is the transverse and L the longitudinal orientation of the plate. Different directions of fracture propagation were used to study the influence of anisotropy on the CTOA toughness values. A schematic of the test specimen is shown in Figure. 7.

The specimens had in plane-dimensions of $200mm \times 100mm$. This allowed large amounts of stable crack growth in their long uncracked ligament. An initial straight notch (2mm width) was placed through the specimen thickness by a saw cutting machining. A 0.5mm sharp crack was introduced at the end of the initial blunt notch using a cutter. The final notch length was 100mm (measured from the centre of the loading pins) resulting in a 0.5 ratio of crack length to specimen width.

To increase the restraint effects ahead of the moving crack and enhance the crack path stability,

Table 1. Measured tensile properties of 2024-T3 aluminium alloy used in this research.

specimen	Young's modulus GPa	Yield strength MPa	Tensile strength MPa
axial	70	282	503
transverse	70	341	512

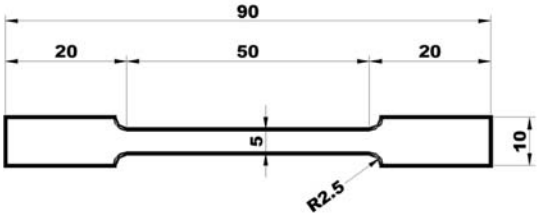

Figure 5. Schematic of tensile specimen with rectangular cross section used in this research.

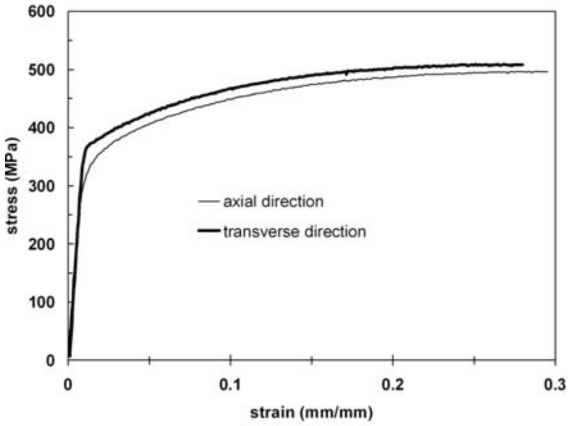

Figure 6. Stress versus strain for tensile specimens taken from axial and transverse direction of the original plate.

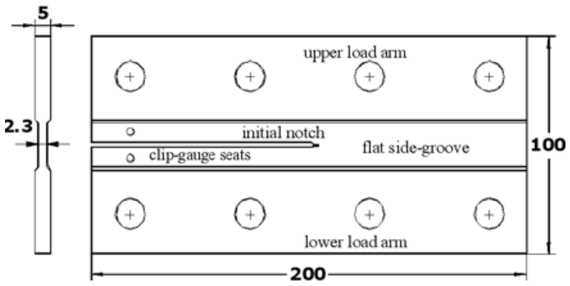

Figure 7. Geometry and design dimensions of tear specimen used in this work.

the thickness of the specimens was reduced from the original 5mm thickness to a gauge thickness of 2.3mm by machining. This resulted in two thicker loading arms and a thinner flat side-grooved region, 20mm high and 200mm long, on opposite sides of each specimen. The flat side-grooved region was used for crack growth study and optical measurement of CTOA values. The loading of the specimen then was conducted using two pairs of thick anti-buckling plates (each with 15mm thick) clamped to the specimen on its side surfaces through four high-strength bolts and nuts. An equal 50kN torque was used to fasten the clamping bolts. This prevented any slippage between the specimen and loading plates during the test. A pair of U-shape grips was made and used to fit the loading plates into the machine fixtures. Two 25mm cylindrical pins provided free rotation of the whole assembly (specimen plus loading plates) during the experiments. The plate grips covered an area of $200mm \times 40mm$ both on the upper and lower parts on each side of the specimen leaving the flat side-groove region out for the purpose of photography.

The thin flat side-grooves together with the two thick loading grips increased the constraint levels in the gauge section of the CTOA specimen. The long uncracked ligament and the loading geometry provided the condition of stable shear crack extension in the specimen ligament similar to that of the real structure. All experiments were conducted on a 600kN Zwick test machine under opening mode I loading conditions. The specimens were steadily loaded at a low strain rate under displacement control of 0.05mm/s. Figure 8 is a photograph of the test set up. In each test the load and ram displacement were recorded by a PC equipped with a data acquisition card and software.

CTOA MEASUREMENT AND MESH SCORING SCHEME

CTOA was measured optically using digital images. The whole cracking process of the specimens was filmed using conventional digital video cameras. A close-up lens of +4 magnification was used to capture high quality images of the growing crack. This allowed the video cameras to be installed as close to test specimens as possible (usually at 20mm distance). High-resolution images of opposite sides of the specimens were registered on digital videotapes during each test. The recording time was automatically available from these. This allowed the subsequent correlation between test parameters such as load, displacement, crack length and CTOA. The resolution of digital video images were 720× 576 pixels. Each image represented 25mm× 15mm of the cracking region. The captured frames were analysed using a computer software analysis package (GIMP version 1.2.4). The CTOA was

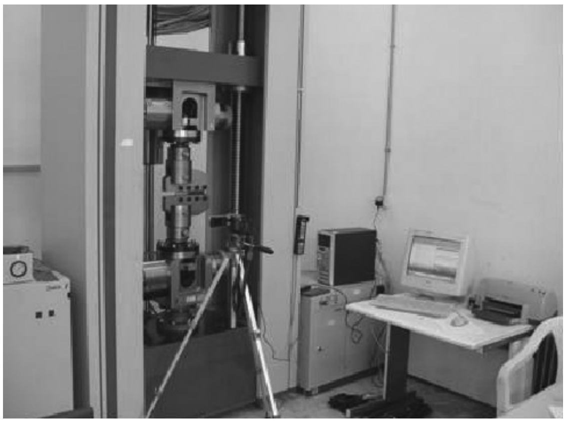

Figure 8. Photograph of the CTOA test set up.

directly measured in each image from the recorded crack opening profile.

Measurement of CTOA was facilitated by scribing a fine mesh with a spacing of 1mm on the side surfaces of each specimen, as shown in Figure 9. To reduce the effect of light reflection a dark matt blue dye (conventional layout ink) was uniformly sprayed on the flat sidegrooved area of the specimens. This was very effective in that it provided the maximum contrast between the crack front boundaries and the scribed gridlines. The thickness of the thin paint layer was 0.02mm. The reference grid was scored on this dark background by a height gauge with 0.01mm accuracy.

During the fracture tests, the originally straight lines near the crack tip were rotated uniformly as the crack grew in the specimen ligament. This was filmed continuously on the typical videos from which fracture events were captured on individual digital frames. The captured images were analysed then at 1mm crack growth intervals. In each image, the crack tip was located and the crack length was measured with respect to the reference grids. The slope of the rotated gridlines was used for CTOA calculation for the 2024-T3 aluminium alloy. Figures 10 and 11 show a fractured specimen and the detail of the CTOA measurement approach.

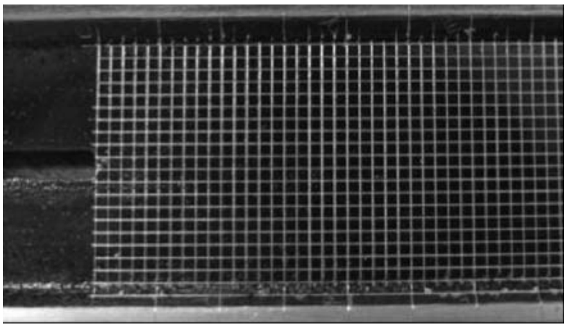

Figure 9. Reference mesh of 1mm spacing on the surface of the CTOA specimen.

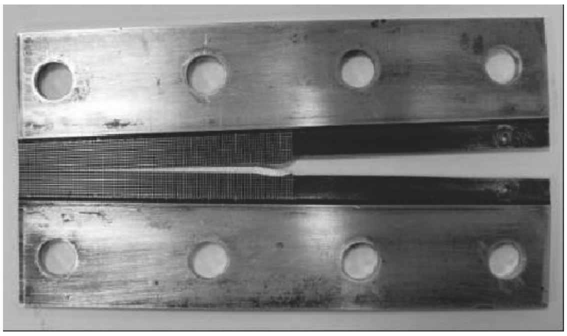

Figure 10. Photograph of a CTOA specimen after fracture test.

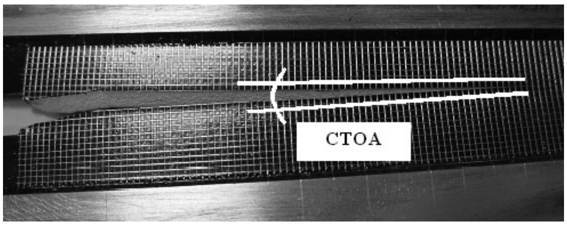

Figure 11. Measurement of CTOA on the specimen surface using reference mesh.

RESULTS AND DISCUSSION

Figures 12 and 13 illustrates the CTOA resistance curves for Al 2024-T3 is the axial and transverse direction, respectively.

From these two CTOA resistance plots the following results can be obtained:

1. The CTOA toughness showed large initiation at the early stage of cracking (between 6 to 8 degree) which rapidly descended to a plateau as the crack grew through the ligament. The large initiation CTOA is associated with flat tearing and crack tunnelling effects (variation of crack length through the thickness) caused by high restraint at the middle section of the specimen. The dropping of CTOA values is due to the transition from flat-to-slant fracture. After the transient regime, the development of slant shearing was completed resulting in a steady crack propagation phase and constant CTOA values.
2. The comparison between the CTOA values measured from the crack edge and from the reference mesh on 2024-T3 aluminium alloy showed that the crack edges produced a value of stable CTOA apparently higher than that obtained from the gridlines. This is primarily due to uncertainty in locating the crack tip and auxiliary points on the crack surfaces for CTOA estimation. The use of the mesh in the deformed specimen resulted in smaller values of CTOA data. The consistency of steady state CTOA values is indicative of the stability of the CTOA monitoring scheme.
3. The CTOA measurement from the deformed mesh resulted in a CTOA value of 3.6° and 3.8° (with less than 0.6° standard deviation) for axial and transverse specimens, respectively. Here the small scatter was primarily caused by the thickness of gridlines (width of the height gauge scriber tip) during the CTOA estimation from captured images under high magnification. Alteration in the meshing technique to reduce the thickness of the gridlines is currently under review.
4. The stable CTOA values measured by reference mesh in the axial direction (3.6°) is slightly less than that of the CTOA in the transverse direction (3.8°). The same is true for stable CTOA values

measured by crack edges (4.2° against 4.6°). This is a result of plate rolling processes during its fabrication.

5. Further evidence for the validity of the measured stable CTOA values of 3.6° and 3.8° in axial and transverse specimens (using reference mesh) can be obtained by FEA of test specimens. Using these critical values, the computer model (based on node release technique) should be able to produce load-displacement data similar to that of the experiment. This is an area worthy of investigation and further research is underway to simulate the test results.
6. The measured stable CTOA for tested aluminium alloy using crack edges (4.2°in axial and 4.6° in transverse direction with less than 1° standard deviation) is comparable with the values of 5.3° and 5.0° (in axial and transverse direction, respectively) for 2024-T3 aerospace aluminium reported by Dawicke [31] and Seshadri *et.al.* [32], and with 4.6° in transverse direction from M(T) specimens with 2.3 mm ligament thickness [22].
7. The CTAO values obtained in the current research are in general slightly less than those reported in references [5,7] for specimens with different geometry and loading conditions but with a similar ligament thickness of 2.3mm. A possible reason for this small difference is that C(T) and M(T) specimens used in those works had an initial gauge thickness of 2.3 mm, whereas the DBC sample of the current research had an initial thickness of 5mm which was reduced to 2.3mm by machining. This gauge thinning might had an effect on the obtained CTOA results.

CONCLUSION

A novel test technique for direct measurement of the steady state CTOA has been presented. Optical imaging was used to register the uniform rotation of a fine grid scored on the sides of a modified double cantilever beam. The technique was used to determine the steady state CTOA values for 2024-T3 aluminium alloy in the axial and transverse directions. In all experiments the approach was able to produce large amounts of highly consistent CTOA data. This extensive data set allowed an evaluation of the variance of the stable CTOA as the crack grows through the specimen. The test method generated a steady state CTOA value of 3.6°, 3.8° (with less than 1° standard deviation) for aluminium alloy in the axial and transverse orientations, respectively.

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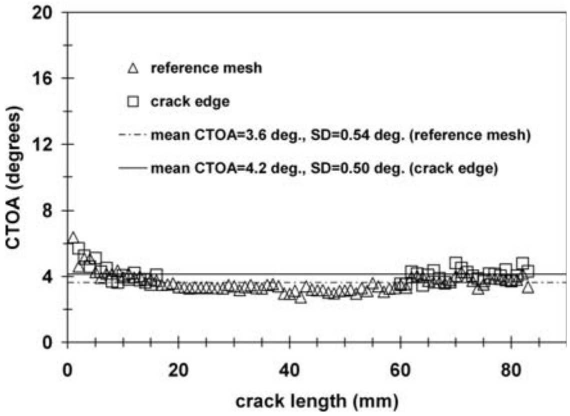

Figure 12. CTOA resistance curve for Al 2024-T3 (crack propagation in plate in axial direction).

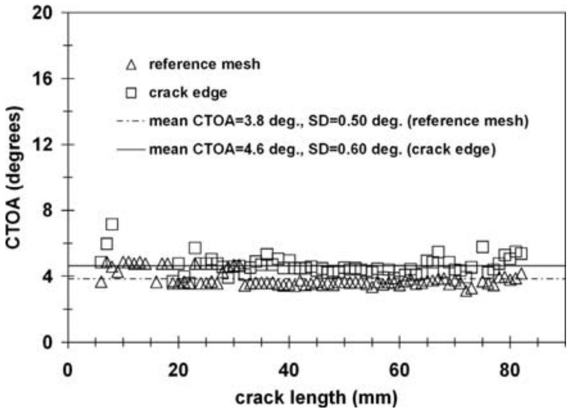

Figure 13. CTOA resistance curve for Al 2024-T3 (crack propagation in plate transverse direction).

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