DEVELOPMENT OF A LABORATORY TEST TECHNIQUE FOR DIRECT ESTMATION OF CRACK TIP OPENING ANGLE

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Summary

Recent experimental work and computational studies on the ductile failure behaviour of high-strength high-toughness materials like aerospace aluminium alloys and gas pipeline steels have shown that Crack Tip Opening Angle (CTOA) can be effectively used to characterise the material fracture resistance in the case of large amounts of stable crack propagation.

One of the main difficulties currently limiting the more extensive use of the CTOA fracture toughness parameter is its practical evaluation, either in the real structure or in a laboratory-scale experiment. Although there are a number of test methods available for CTOA calculation, their implementation requires a combined test and finite element analysis and the use of experimental load-deflection data for tuning processes.

The authors have recently developed a novel laboratory test technique for direct measurement of the critical CTOA. Fracture tests are conducted on a modified double cantilever beam like specimen. The test samples have a long ligament to allow extensive crack growth and flat side-grooves of large dimension to facilitate photography of the progressing crack tip. A fine mesh is scribed on the side-groove on both sides of the specimen for accurate study of the crack opening profile. Optical imaging is used to register the uniform deformation of the reference mesh during the fracture experiment. The variation of the slope of the deformed gridlines near the progressing crack tip is measured from captured images. Its value is a representative of the material CTOA.

So far the method has been successfully used to determine the steady state CTOA of aluminium alloy (6005A T6) used in railway carriages and gas pipeline steels of grade API X80 and X100. In each case the test approach was able to generate highly consistent CTOA data even from a single specimen. The extensive data set allowed the statistical analysis of the variance of the measured CTOA. The computed stable CTOA was 4.1^o, 11.1^o and 8.5^o (with less than 1° standard deviation) for aluminium alloy, X80 and X100 grade line pipe steel, respectively.

This paper presents the results from the implementation of the technique to measure the steady state CTOA of 6005A T6 aluminium alloy. It outlines the design geometry of the testpieces and the procedure used for CTOA computation, and provides a discussion of the obtained results and a comparison between the measured stable CTOA values and the available CTOA data.

Introduction

Ductile fracture is the 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 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 [1-3]. It 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 [4-6], gas pipeline [7-9] and high pressure vessels steels [10] 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 is currently under review.

Comprehensive research [4-6] on the CTOA profile of spacecraft aluminium alloys has been conducted at NASA Langley by Newman, Dawicke and their co-workers. In this work, large dimension thin and thick C(T) and M(T) specimens of varying thicknesses ranging from 1 to 25.4mm were tested at low strain rates. Optical techniques were used to monitor the progression of the crack tip. 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, see Fig. 1.

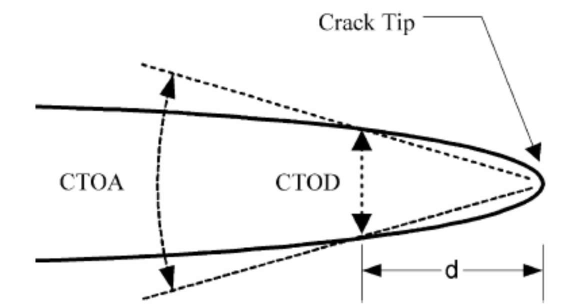

FIGURE 1. Definition of Crack Tip Opening Displacement (CTOD) and CTOA measurement scheme from reference [11]

Equation (1) was used to calculate the CTOA data during the crack growth:

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

To remove the dependency of measured CTOA values on the distance d, CTOA is usually estimated over a distance of 0.5 to 1.5mm behind the crack tip and its mean value is used [4-6]. 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 a 25mm thickness range for 2024-T351 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 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 and the comparison of the obtained data on a 3mm thick A15083 H321 aluminium alloy with the results from optical imaging can be found in reference [12]. 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 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 available results for gas pipeline steels of grades X70 to X100 have indicated a similar CTOA profile. A high initiation CTOA which rapidly dropped to an invariant value during the stable phase of crack propagation has been observed in all experiments. The constant CTOA value is considered as the material fracture resistance, and compared with the fracture driving force from the escaping gas in a burst event according to the following relationship. Whenever the inequality (2) is fulfilled, any possible fracture should be arrested in the pipeline.

$$CTOA_{material} > CTOA_{applied} \quad (2)$$

Different CTOA measurement procedures have been used to derive the CTOA resistance of pipeline materials. For instance, Demofonti, Kanninen, Mannucci and their colleagues developed the standard two-specimen CTOA test method based on the specific fracture energy concept and a computer code for evaluating the material and the applied CTOA values, respectively [13,14]. Other experimental techniques such as high-speed photography in dynamic drop weight tear test [9], the specimen arm rotation around the instantaneous centre of rotation in 3PB specimens [15], the reconstruction of the fracture flap angle from the displacement field behind the crack tip using strain gauges in full-scale burst tests [16], and CTOA estimation from the deformed mesh in a single CTOA test approach [17] have been used for this purpose. Recent developments in the latter CTOA test method are described here.

The technique is used for direct measurement of the CTOA data in a laboratory scale test and 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.
- it measures the CTOA from a deformed mesh, and hence removes the uncertainty in locating the crack tip and identifying the curved crack profile in similar CTOA estimating approaches.
- as the deformed 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.

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 obtained for pipeline steels of grade X80 and X100 have been reported elsewhere [17,18]. This paper reports recent results from CTOA testing on 6005A T6 aluminium alloy used in railway vehicles [19] and compares the measured stable CTOA values with the available data from the literature.

Material properties

The material mechanical properties were measured on three round tensile bars of 40mm gauge length and 5mm gauge diameter in longitudinal direction of 6005A T6 aluminium plate. All experiments were performed on a servo-hydraulic Instron 8501 test machine under displacement control of 0.01mm/s. The measured Young's modulus, yield and tensile strength of the material were 70 GPa, 255 and 283 MPa, respectively.

Table 1 contains the chemical composition of the aluminium.

TABLE 1. Chemical composition of 6005A T6 aluminium alloy

element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other/each	other/total	Al
(wt%)	0.5-0.9	0.35	0.3	0.5	0.4-0.7	0.3	0.2	0.1	0.05	0.15	rest

CTOA specimens

A modified double cantilever beam (DCB) specimen was used to conduct the fracture tests. A schematic of the test specimen is shown in Fig. 2.

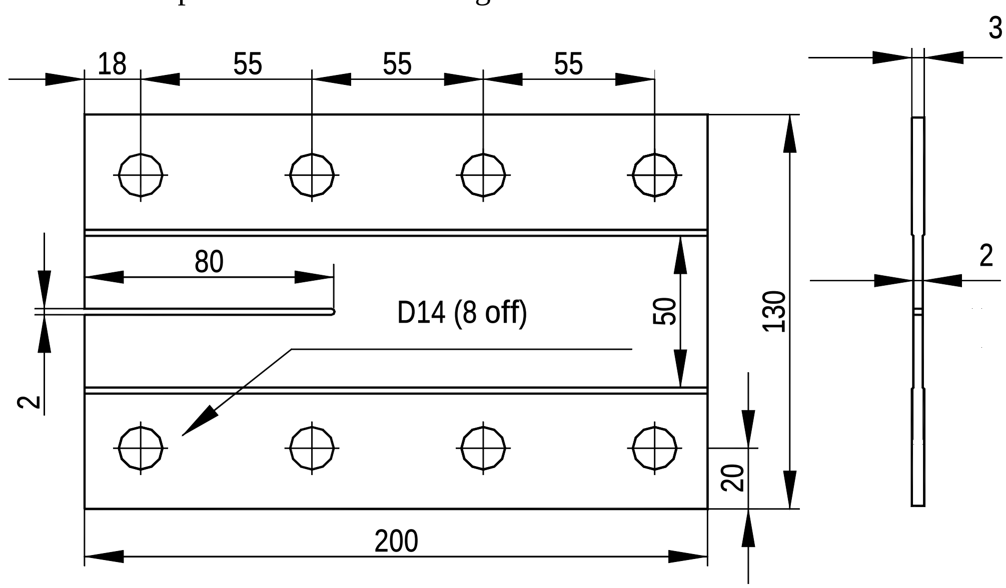

FIGURE 2. Geometry and design dimensions of tear specimen used in this work

CTOA specimens were taken from the same plate in the T-L orientation, where T is the transverse and L the longitudinal orientation of the plate. The generous in-plane dimensions of the specimens $(200mm \times 130mm)$ and the long ligament length allowed large amounts of stable crack growth. An initial straight notch (2mm width) was placed through the specimen thickness by wire cutting machining. The notch length was 62mm (measured from the centre of the loading pin) resulting in a 0.3 ratio of crack length to specimen width.

To increase the restraint effects in the specimens, the gauge thickness of the specimens was reduced from the original 3mm thickness to 2mm by machining. This resulted in two thicker loading arms and a thinner flat side-grooved region, 50mm 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.

Extensive experimental work on X80 and X100 steel showed that the loading of the specimen through one pair of loading pins in conventional DCB testing increased the risk of specimen buckling. This was promoted by the long ligament in the specimen and the thin gauge thicknesses. To resolve this, extra holes were drilled in the specimen arms. The loading of the specimen then was conducted using a pair of thick plate grips on the side surfaces. Two 20mm cylindrical pins provided free rotation of the whole assembly (specimen plus loading plates) during the experiments.

The thin flat side-grooves together with the two thick loading grips increased the constraint levels in the gauge section. 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 250kN Schenck 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. In each test the load and load line displacement were recorded. Fig. 3 is a photograph of the test set up.

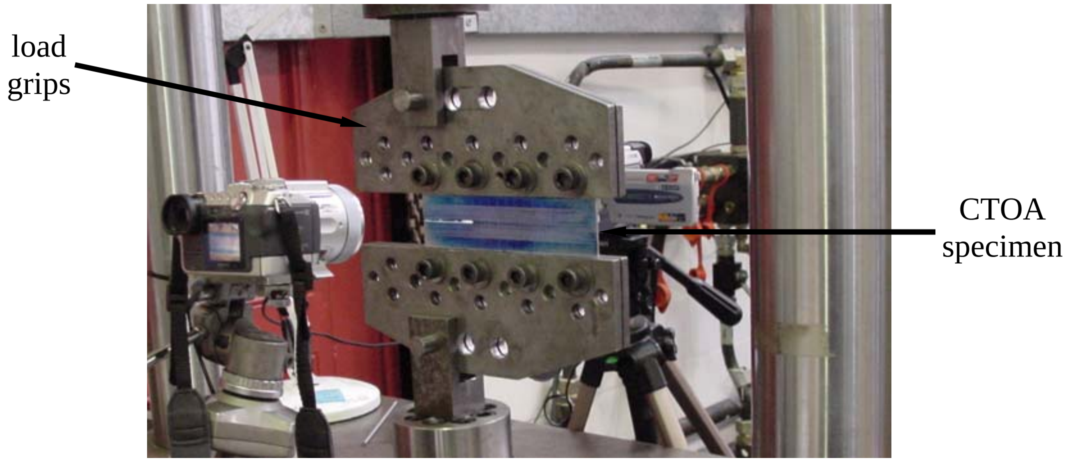

FIGURE 3. Photograph of the CTOA test set up

CTOA measurement scheme

CTOA was measured optically using digital images. The whole cracking process of the specimens was filmed and photographed using a digital video camera and a 5 mega pixels digital still camera. A close-up lens was used to capture high quality images of the growing crack. High-resolution images of opposite sides of the specimens were registered on digital videotapes and memory cards during each test. The recording time was automatically available from the videotapes whereas a digital stopwatch was used to synchronise the still images. This allowed the 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 $25\text{mm} \times 15\text{mm}$ of the cracking region. The still camera images had a resolution of 2240×1680 pixels and showed $50\text{mm} \times 35\text{mm}$ of the specimen surface. The captured frames were analysed using a computer software analysis package (GIMP version 1.2.4). The CTOA was 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 inline with the predicted crack path on the side surfaces of each specimen. To reduce the effect of light reflection a dark matt blue dye was uniformly sprayed on the flat sidegrooved area of the specimens. The reference grid was scored on this dark background by a height gauge with 0.01mm accuracy. The captured images of the aluminium specimens were analysed at 2mm crack growth intervals. In each image, the crack tip was located and the crack length was measured with respect to the reference grids. The deformed mesh was used for CTOA calculation. During the crack growth, the originally straight lines near the crack tip were deformed to inclined lines. The angles of these gridlines were measured during the cracking process as representative of the CTOA of 6005A T6 aluminium alloy. Fig. 4 shows a fractured specimen and the detail of the CTOA measurement approach.

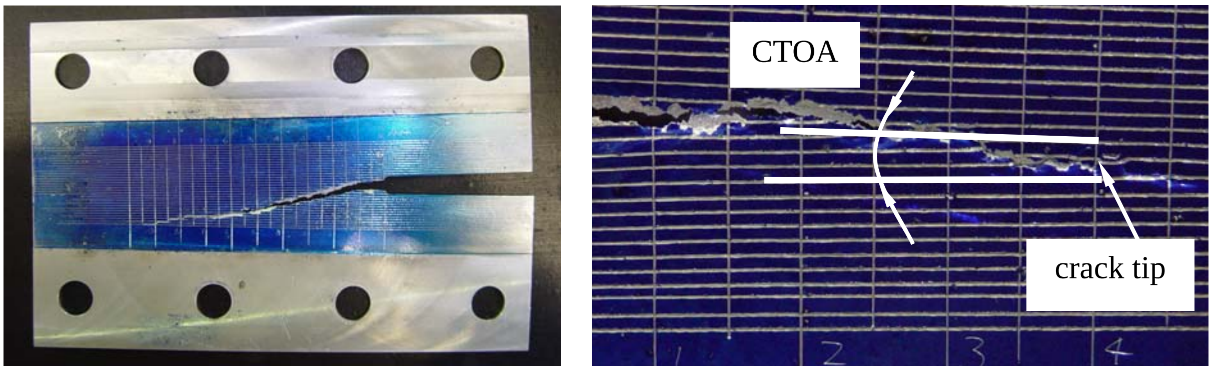

FIGURE 4. Photograph of a fractured specimen and the CTOA estimation scheme

Results and discussion

Fig. 5 illustrates the CTOA resistance curves for high toughness pipeline steel of grade API X80 taken from previously published work [17] and the new results for 6005A T6 aluminium alloy measured on a 2mm gauge thickness specimen using the first set of gridlines.

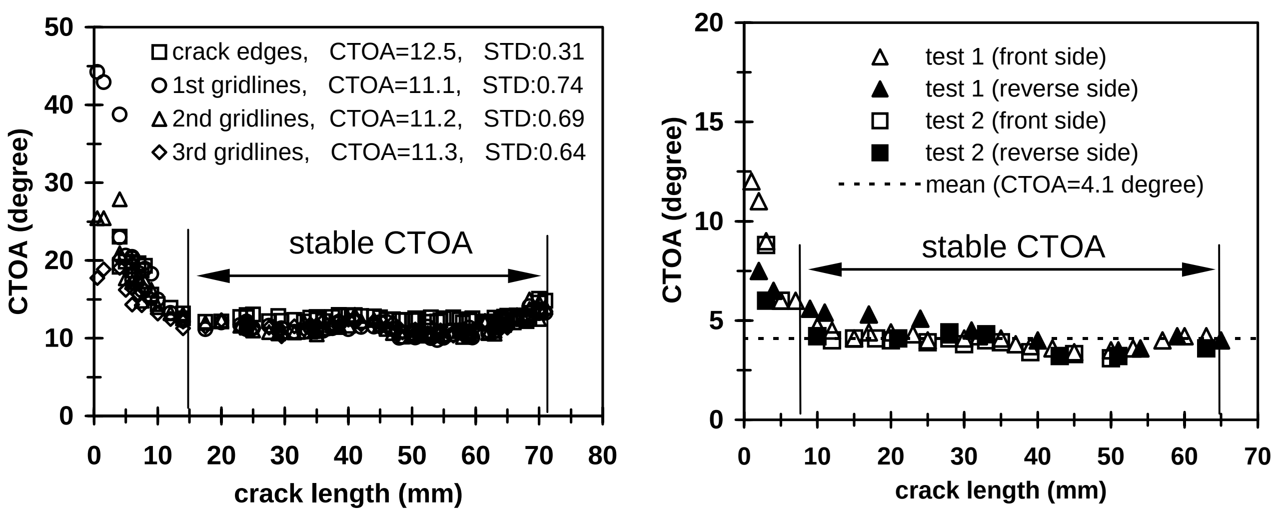

FIGURE 5. CTOA resistance curves for X80 steel (left) and
6005A T6 Aluminum alloy (right)

The comparison between the CTOA values measured from the crack edges and from the first, second and third pairs of gridlines on the X80 specimen showed 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.

A similar CTOA profile was observed for 6005A T6 aluminium alloy. The CTOA toughness showed large initiation at the early stage of cracking (about 12^o) 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.

The CTOA measurement from the deformed mesh resulted in a CTOA value of 4.1^o and standard deviation of $\pm 0.4^o$. 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.

The measured stable CTOA for 6005A T6 aluminium alloy is comparable with the value of 5.24^o ($\pm 1^o$ scatter band measured on a 2.3mm thick specimens) of 2024-T351 aerospace aluminium [11] and 5^o (from a 3mm thick specimens) of AL5083 H321 [12], despite the differences in specimen geometry and microstructure.

The large quantity of CTOA values (almost 60 data point) made it possible to evaluate the variance of scatter of the test results. Fig. 6 shows the distribution of normal probability of the steady state CTOA from tear testing of the 6005A T6 aluminium alloy specimens. It indicated that there was less than 0.2% probability of the CTOA being less than 3°.

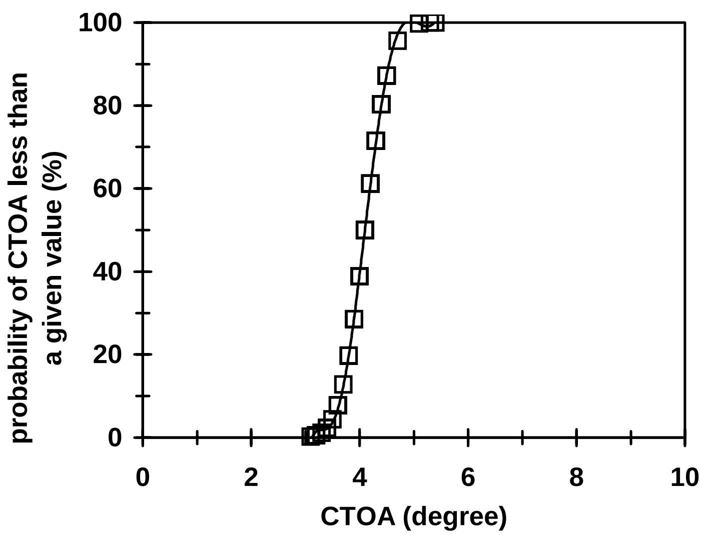

FIGURE 6. Normal probability plot of CTOA data for 6005A T6 aluminium alloy

Conclusion

A novel test technique for direct measurement of the steady state CTOA has been presented. Optical imaging was used to register the uniform deformation of a fine grid scored on the sides of a modified double cantilever beam. The technique was used to determine the steady state CTOA of 6005A T6 aluminium alloy as well as gas pipeline steels of grade API X80 and X100. 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 4.1^o, 11.1^o and 8.5^o (with less than 1° standard deviation) for aluminium alloy, X80 and X100 grade line pipe steel, respectively.

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