EXPERIMENTAL DETERMINATION OF CTOA TOUGHNESS

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ABSTRACT

Crack Tip Opening Angle (CTOA) has been proposed as the controlling parameter during stable ductile crack propagation. A major difficulty currently limiting more extensive use of a CTOA based fracture methodology is the practical measurement of CTOA toughness values either in a real structure or in a laboratory-scale test. Although a number of CTOA estimation methods are now available, their use require combined test and computer tuning processes using experimental load-deflection data from laboratory specimens. An experimental CTOA estimation approach has been recently developed by the authors of the present paper to directly capture CTOA data from a small-scale test. The technique uses imaging systems to register the progression of the moving crack tip on the faces of a modified double cantilever beam (DCB). The full CTOA profile is evaluated from the uniform variation of the slope of a reference grid scored on the sides of the CTOA specimen. This provides a continuous evaluation of CTOA values versus crack length during the fracture experiment from which highly consistent CTOA data can be achieved. This extensive data set allows statistical analysis of the variance of the measured CTOA values. The paper contains the results from the application of the new test approach for CTOA measurement of high-strength pipeline steels of grade API X80 and X100 as well as a 6000 series aluminium alloy used in railway carriages. The computed stable CTOA was 11.1^{o}, 8.5^{o} and 4.1^{o} (with less than 1^{o} standard deviation) for X80 and X100 steels and aluminium alloy, respectively.

1 INTRODUCTION

Ductile fracture is a major failure mechanism in engineering materials and structures. Among several fracture criteria proposed for characterising this fracture mode, it has been shown that CTOA has the promise for assessing the ductile rupture resistance of high-toughness materials [1-3]. Extensive study of CTOA properties of aerospace materials [4,5], gas pipeline [6-8] and high pressure vessels steel [9] has revealed that CTOA can be regarded as a material constant over the stable crack propagation phase. It can be directly measured from the crack opening profile, related to the geometry of the fracturing structure, and implemented easily in FE models of the propagating fracture process.

The study of the CTOA data in ductile failure has shown that initial flat tearing and crack tunnelling results in high CTOA values in the early stages of cracking. After the transitions from flat-to-slant fracture, the CTOA values stabilise. In the stable slant-cracking phase a steady state CTOA value can be considered as a material property. It might be subsequently implemented in ductile failure arrest/propagation models as a fracture controlling parameter.

Different CTOA measurement procedures have been used to derive the CTOA resistance of materials. For instance, Newman, Dawicke and their co-workers used optical techniques to estimate the CTOA toughness of 2024-T351 spacecraft aluminium alloys in large C(T) and M(T) specimens [4-6]. Similar work has been conducted on a 3mm thick A15083 H321 aluminium alloy by Heerens and Schodel [10] using an alternative δ_5 technique. The results of these studies are used in this research for the purpose of comparison.

In the gas pipeline industry, the pioneering work of Demofonti, Venzi, Kanninen, Salvini and their colleagues resulted in a two-specimen CTOA test method as well as a computer code for evaluating the CTOA of the material and the applied CTOA values, respectively [11,12]. Other experimental techniques such as high-speed photography in dynamic drop weight tear tests [13], the specimen arm rotation around the instantaneous centre of rotation in 3PB specimens [14], the reconstruction of the fracture flap angle from the displacement field behind the crack tip using strain gauges in full-scale burst tests [15], and CTOA estimation from the reference mesh in a single CTOA test approach [16] have been used for this purpose. Recent developments in the latter CTOA test method are described here.

The new CTOA test technique measures the value of CTOA directly from a laboratory-scale test and has the following features:

- it provides large amounts of highly consistent CTOA data from one experiment.
- the extensive CTOA data set provides statistics on the scatter of measured CTOA values.
- it measures the CTOA from a reference 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.
- it removes the necessity of repetative calculations of the CTOA at different distances behind the crack tip and subsequent averaging of the measured CTOA values.

2 CTOA SPECIMEN DESIGN AND OPTIMISATION

A modified DCB specimen was used in the CTOA experiments [16]. While the uncracked ligament of the conventional fracture mechanics specimens is too short, the generous in-plane dimensions of the DCB and its long ligament allows large amounts of stable crack growth. In order to manufacture the DCB specimens plates were cut from the X80 and X100 pipes and flattened by machining. This removed the pipe curvature without introducing pre-strains in the test samples from straightening. All DCB specimens were taken from these plates in the TL direction (where T is the circumferential and L is the longitudinal orientation of the pipe). The aluminium specimens were extracted from an original 3mm thick plate with the initial notch oriented in the plate rolling direction. To increase the restraint ahead of the crack tip, the gauge thickness of the specimens was reduced by machining (to 8, 10 and 12mm in the gas pipeline steels and to 2mm in the aluminium specimens) resulting in a flat side-groove on the sides of each specimen. The flat side-grooved region was used for crack growth study and optical measurement of CTOA values. Loading of the specimen then was conducted using a pair of thick plate grips on the side surfaces. The thin flat side-grooves together with the two thick loading grips increased the constraint levels in the gauge section. This provided the condition of stable shear crack extension in the specimen ligament similar to that of the real structure.

3 CTOA MEASUREMENT TECHNIQUE

The CTOA was measured optically using digital images. High-resolution images of opposite sides of the specimens were recorded on digital videotapes and memory cards during each test. The captured frames were analysed using computer software (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 on the side surfaces of each specimen. To reduce the light reflection effects a dark matt blue dye was uniformly sprayed on the flat side-grooved area of the specimens. The reference grid was scored on this dark background by a height gauge with 0.01mm accuracy.

During the crack growth, the originally straight gridlines near the crack tip were rotated to inclined lines. The angles of these gridlines were measured during the cracking as representative of the CTOA data. The detail of the CTOA estimation technique is shown in Fig. 1. This figure compares the conventional CTOA measurement method from the crack front and the new CTOA estimation technique using the reference grid.

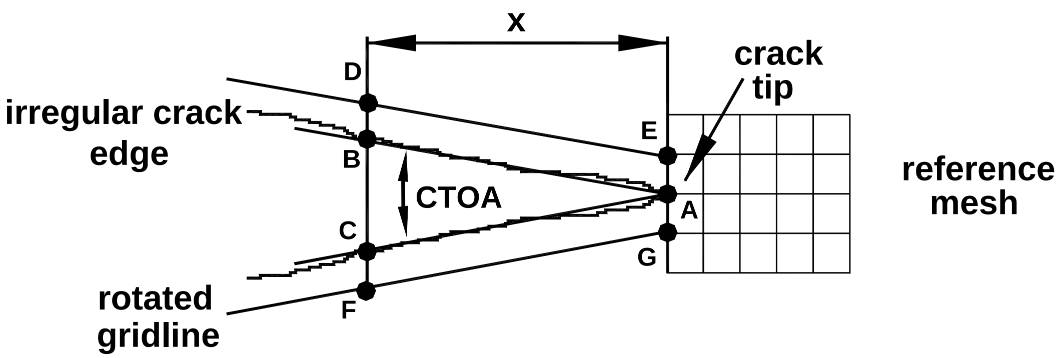

Figure 1: Determination of CTOA from the crack flanks and from the slope of the reference mesh

The estimation of the CTOA values from crack edges is conducted using the following procedure. First the crack tip (marked as point A in Fig. 1) and two adjacent points on crack edges (B and C) are located at a fixed distance x behind the crack tip. Next two straight lines (AB and AC) are fitted on the curved crack front. Then the value of CTOA is calculated in triangle ABC from CTOA=$2\tan^{-1}(BC/2x)$. Extensive work on aluminium alloy [3-5] has shown that values of x between 0.5 to 1.5mm generated consistent CTOA data in the steady state phase of crack growth. However an average of the CTOA values measured at different x distances in each image has been recommended to minimise the dependency of CTOA data on this variable.

Due to the irregular crack profile, accurate positioning of the crack tip and the two auxiliary points on the crack front is somewhat problematic. This results in a scatter in the measured CTOA values of the order of $\pm 1^o$ [4,5]. In the new technique however the CTOA is estimated from the reference gridlines near the crack tip. The curved crack opening profile is approximated by two straight lines (ED and GF) on the first set of gridlines. The CTOA is estimated in each image from the angle of these grid lines and considered as representative of the CTOA of the material.

4 MATERIAL PROPERTIES

Two gas pipeline steels of grade API X80 (48” O.D× 13.8mm W.T) and X100 (36” O.D×19mm W.T) and a 6000 series aluminium alloy were tested. The mechanical properties of the steels and aluminium alloy are set out in Table 1.

Table 1: Mechanical properties of tested materials in transverse orientation

MATERIAL	E (GPa)	σ_Y (MPa)	σ_u (MPa)	σ_Y / σ_u
X80	210	546	686	0.80
X100	210	769	823	0.93
6005A T6	70	255	283	0.90

5 EXPERIMENTAL RESULTS AND DISCUSSION

All experiments were conducted under opening mode I loading conditions at a low strain rate of 0.05mm/s. Fig. 2 is a photograph of the test set up.

Figure 2: View of a CTOA specimen with 8mm ligament thickness after fracture

Figs. 3 and 4 illustrate the CTOA resistance curves for tested materials.

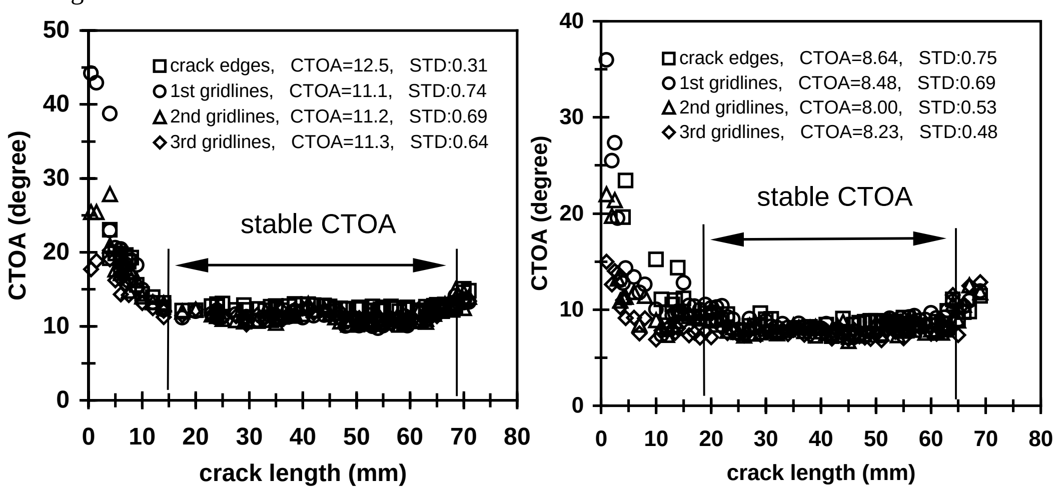

Figure 3: CTOA resistance curves for X80 (left) and X100 steel (right)

The CTOA data of X80 steel has been taken from previously published works [16]. The comparison between the CTOA values measured from the crack edges and from the first, second and third pairs of gridlines on the X80 and X100 specimens showed the crack edges produced values 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 specimens resulted in smaller values of CTOA data: $11.1^o \pm 0.74^o$ and $8.5^o \pm 0.69^o$ for X80 and X100, respectively. Here the 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. The CTOA data reported here agrees well with the available CTOA values in the literature for similar steels [11-15].

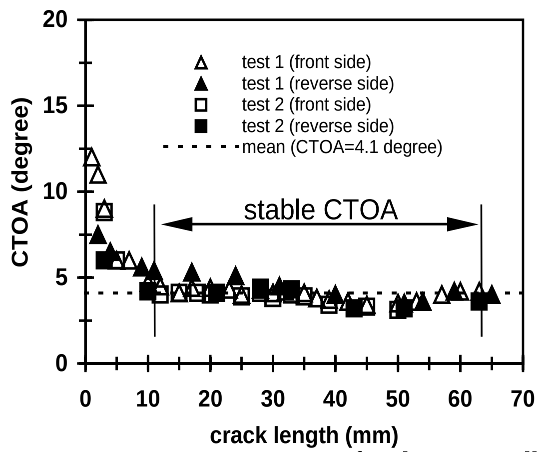

Figure 4: CTOA resistance curve for aluminium alloy

The CTOA toughness values of aluminium showed large initiation (about 12^o) at the early stage of cracking which rapidly descended to a plateau of 4.1^o ($\pm 0.4^o$ standard deviation) as the crack grew through the ligament. The measured stable CTOA for 6005A T6 aluminium alloy specimens (having 2mm ligament thickness) 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 [5] and 5^o (from a 3mm thick specimens) of AL5083 H321 [10], despite the differences in specimen geometry and microstructure.

6 CONCLUSIONS

A novel test technique for direct measurement of the steady state CTOA has been presented. The method was used to determine the stable CTOA values of gas pipeline steels of grade API X80 and X100 as well as 6005A T6 aluminium alloy specimens. 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 grew through the specimen ligament. The test method generated a steady state CTOA value of 11.1^o, 8.5^o and 4.1^o (with less than 1^o standard deviation) for X80 and X100 steels and aluminium alloy, respectively.

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