EXPERIMENTAL DETERMINATION OF THE CRITICAL CRACK TIP OPENING ANGLE (CTOA) USING THE CTOD δ_5 MEASUREMENT TECHNIQUE.

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ABSTRACT

Crack tip opening angles, CTOA, of stably growing cracks in 3mm thick Al 5083 sheet material were determined using light microscopy and the δ_5 clip gauge technique. Several types of specimens such as C(T), M(T) and cruciform specimens were considered. After a short transition regime the crack propagates in all specimens with a constant crack tip opening angle of 5 degrees. This observation supports that the CTOA is a useful parameter for characterising stable crack extension in sheet material. Applications of the δ_5 clip gauge technique have shown that the slope of the C(T) δ_5 R-curves agrees well with optically determined CTOA-data. This result indicates that δ_5 measurements on C(T) specimens are well suited to determine a meaningful CTOA for the characterisation of stable crack extension in thin sheet material. The results support the validity of the δ_5 measurement technique as implemented in the present draft ISO Standard (ISO/TC164/SC).

1 INTRODUCTION

Due to the demands for saving energy in transportation systems, the exploitation of lightweight structures has become increasing importance during the last years. Many lightweight structures are made of Al sheet material, for example the fuselage of aeroplanes, the hull of ships or the wall of storage tanks. Large structures can have large critical crack lengths. As a result, failure of these structures is frequently related to the development of large amounts of crack extension and large scale yielding. In such cases the application of the K-concept and the J-integral concept provides very limited results.

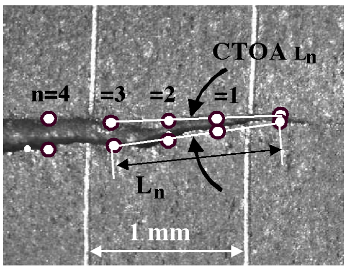
Previous work [1,2] has shown that for elastic ideally-plastic materials the strains at the tip of an extending crack are characterised by the crack tip opening angle (CTOA). This bears the hope that a CTOA based fracture mechanics concept can be developed, particularly useful for failure assessment of light-weight structures.

An important part in the development of a CTOA fracture concept is the provision of reliable experimental methods for the determination of a material specific critical CTOA from laboratory specimens. Presently an ISO Standard (ISO/TC164/SC) is being drafted on this subject. It covers the experimental determination of a critical CTOA using optical methods, digital image correlation methods, microtopographic methods and the δ_5-clip gauge technique, which was developed at GKSS [3]. In relation to a successful dissemination and application of the ISO standard, additional validation work on the experimental determination of CTOA in laboratory specimens is an important prerequisite. In this paper, results on size and geometry effects on CTOA and recent experience on experimental CTOA determination using optical methods and δ_5-clip gauge technique will be presented.

2 RESULTS AND DISCUSSION

Figure 1 shows the GKSS procedure used for determining optical CTOA-data using micrographs, taken at the crack tip of an extending crack in Al 5083 sheet material. C(T), M(T) and biaxially loaded cruciform specimens made from 3 mm thick Al 5083 sheet material were considered. In Figures 2 and 3 it can be seen that the optically determined crack tip opening angles, CTOAopt, are not significantly affected by the specimen size and specimen geometry. In all types of specimens, the $CTOA_{opt}$ approaches a constant value of 5 degrees after some mm of stable crack extension.

$$CTOA_{opt} = \overline{CTOA\ L_n}$$



$0.25mm < Ln < 1.5mm$
$4 < n \leq 6$

Figure 1: Crack tip on the specimen surface and optical determination of CTOA.

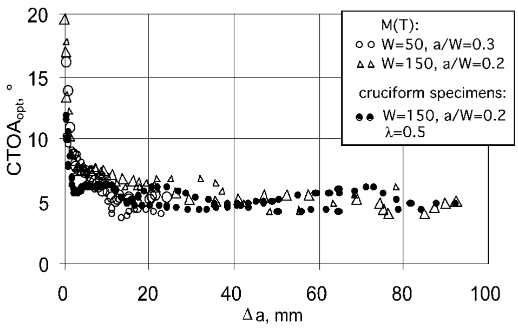


Figure 2: $CTOA_{opt}$ in M(T) and biaxialy loaded cruciform specimens.
(λ is the biaxiality ratio)

Optical methods for the determination of CTOA are time consuming, require costly experimental equipment and its application is rather complex. During the last decades the GKSS has developed the Engineering Treatment Model (ETM) [4,5]. The ETM uses the crack tip opening displacement (CTOD), δ_5, as a parameter to characterise stable crack extension.

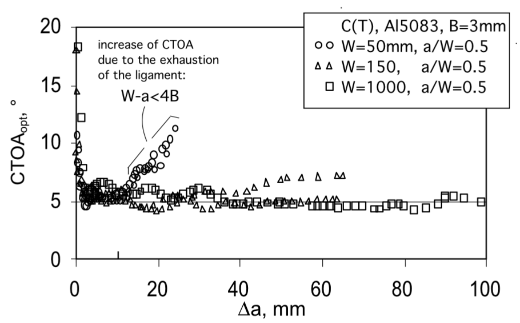


Figure 3: $CTOA_{opt}$ in C(T) specimens.

Figure 4 presents a schematic of the δ_5 measurements technique at the crack tip. As illustrated, an increment of stable crack extension, Δa, causes a crack tip opening displacement, CTOD, as well as an increment of δ_5. If the increment of δ_5 is equal to CTOD, then the crack tip opening angle CTOA is given by the slope of the δ_5 crack resistance curve:

$$CTOA_{\delta 5} = d\delta_5/d\Delta a \qquad [rad] \qquad (1)$$

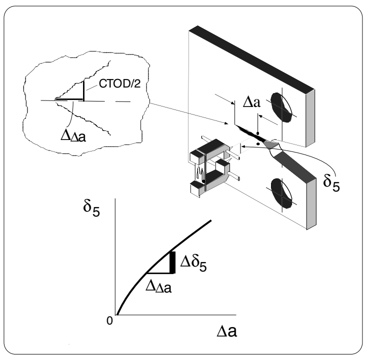


Figure 4: δ_5 measurement technique and schematic of the relationship between the slope of the δ_5 R-curve and CTOA.

In [3] promising results were obtained by using the assumption given by Eq.1. In order to further validate the method, the slope of δ_5 R-curves of M(T) and C(T) specimens with different size have been analysed. The R-curves are shown in Figure 5. The $CTOA_{\delta 5}$ results obtained from the R-curves of C(T) specimens are presented in Figure 6a in detail. The $CTOA_{\delta 5}$-data show a pronounced minimum regime at which $CTOA_{\delta 5}$ has a level of about 5 degrees. This is similar to the CTOA-values obtained by the optical measurement as it is confirmed by a direct comparison of $CTOA_{opt}$ and $CTOA_{\delta 5}$ shown Figure 6b. In Figure 6a it can also be seen that $CTOA_{\delta 5}$ shows a strong upswing if crack extension exceeds the limit of $\Delta a=(W-a_o)0.25$ which is the crack extension limit to valid δ_5 R-curves as required by the GKSS test method [6] and the draft ISO standard. Beyond this limit the formally derived $CTOA_{\delta 5}$ data become much larger than the optically determined CTOA-data. For this reason is not useful to apply Eq.1 in the regime $\Delta a>(W-a_o)0.25$.

In case of M(T) specimens the $CTOA_{\delta 5}$ data show a continuous decrease with increasing stable crack extension and $CTOA_{\delta 5}$ becomes significantly smaller than $CTOA_{opt}$. Figure 7 shows a direct comparison between $CTOA_{\delta 5}$ and $CTOA_{opt}$. This result shows that M(T) specimens do not seem to be appropriate for deriving meaningful CTOA data on the basis of Eq. 1.

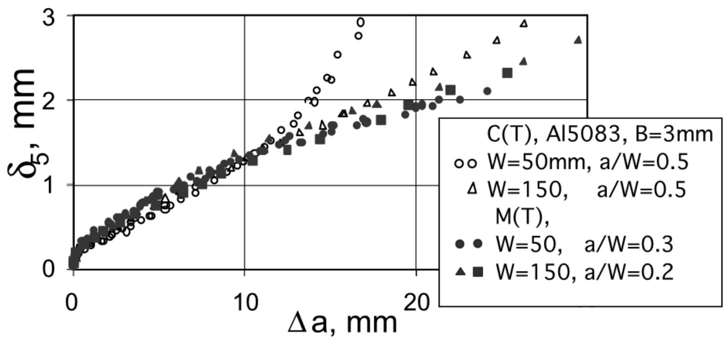


Figure 5: δ_5 R-curves of C(T) and M(T) specimens.

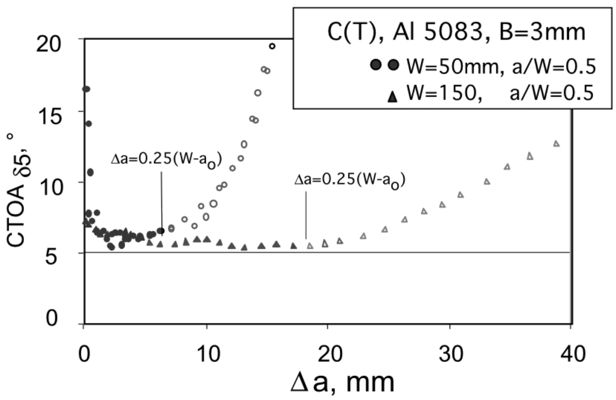


Figure 6a: CTOA data derived from the slope of the δ_5 R-curves of C(T) specimens.

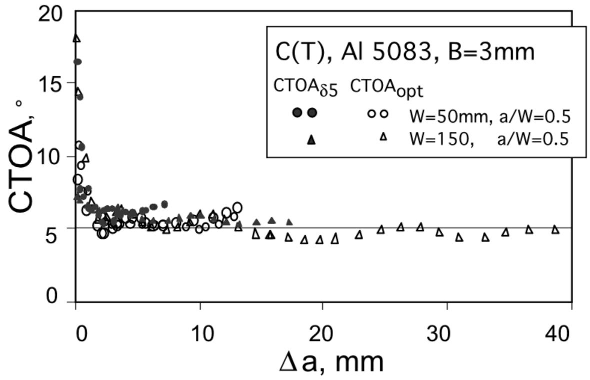


Figure 6b: Comparison of CTOA data obtained from C(T) specimens using optical measurements and the slope of the δ_5 R-curves.

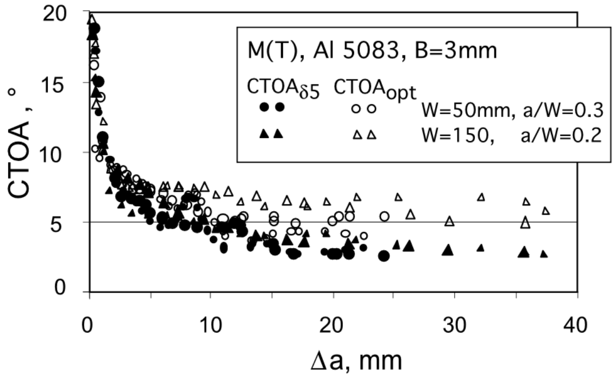


Figure 7: Comparision of CTOA data obtained from M(T) specimens using optical measurements and the slope of the δ_5 R-curves.

The results presented in this paper have been derived from a single material and it was demonstrated that Eq.1 provides reliable CTOA results. Eq.1 has been derived from a simple mechanical model, which does not take into account any material specific quantities such as the stress-strain curve of the material. In order to broaden the experience GKSS is presently investigating the behaviour and experimental determination of CTOA on other types of materials.

3 CONCLUSIONS

The CTOA related to stable crack extension in 3mm thick Al5083 sheet material was experimentally investigated using C(T), M(T) and cruciform specimens. Optical methods and the δ_5 clip gauge technique were applied to determine CTOA data. The results are as follows:

- The CTOA data, which are determined from micrographs of the crack tip at the specimen surface are not significantly affected by the specimen size and specimen geometry. In all types specimens, the $CTOA_{opt}$ approaches a constant value of 5 degrees after some mm of stable crack extension.
- Within the regime $\Delta a<0.25(W-a_o)$ the slope of the δ_5 R-curve of C(T)-specimens coincides with optically determined CTOA data.
- The results support the validity of the δ_5 measurement technique as a part of the draft ISO Standard for the determination of a meaningful CTOA, which characterises stable crack extension in thin sheet material.

4 REFERENCES

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