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CHARACTERIZATION OF STABLE CRACK EXTENSION IN ALUMINIUM-SHEET MATERIAL USING THE CRACK TIP OPENING ANGLE DETERMINED OPTICALLY AND BY THE $\delta_5$ CLIP GAUGE TECHNIQUE.

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ABSTRACT
Tests standards aimed at deriving fracture toughness data and crack resistance curves under low constraint condition have recently been finished by ASTM and are in the final stage within ISO. These standards cover various experimental methods for determining critical crack tip opening angles, CTOA, for characterising stable crack extension in sheet material. In this paper, some key items of these standard methods are validated, namely the experimental determination of the crack tip opening angle by optical observation and using the $\delta_5$-clip gauge method. When applying such standard methods to material characterization it is of particular interest to know how CTOA data derived by different methods compare to with each other. This paper compares CTOA data as derived by the optical method with that derived by using the $\delta_5$-clip gauge method. In order to study possible specimen size and geometry effects the methods have been applied to a wide range of specimen geometries. The results demonstrate that CTOA data derived by the optical method are well suited to provide a specimen size and geometry independent characterization of stable crack extension where the thus obtained CTOA data are constant over a large amount of stable crack extension. In contrast to this result, CTOA-data obtained from the $\delta_5$ clip gauge method revealed a complex pattern of size and geometry effects, and only in case of compact specimens with a selected size the two CTOA-methods provide nearly identical CTOA-data over a large amount of crack extension.

Keywords:
Crack tip opening angle; Stable crack extension, Size and geometry effects; Aluminium sheet material
NOMENCLATURE

- **a**: crack length
- **a₀**: crack length after pre-cracking
- **Δa**: amount of stable crack extension
- **ΔΔa**: increment of stable crack extension
- **Δa_{max,CTOA}**: limit for CTOA controlled crack extension
- **Δa_{max,M(T), R-curve}**: limit for δ₅ controlled crack extension in M(T)-specimens
- **Δa_{max,C(T), R-curve}**: limit for δ₅ controlled crack extension in C(T)-specimens
- **B**: specimen thickness
- **CTOA**: crack tip opening angle
- **CTOA_{opt}**: crack tip opening angle derived microscopically
- **CTOA₅₅**: crack tip opening angle derived using the δ₅ clip gauge technique
- **CTOD**: crack tip opening displacement measured between the crack flanks
- **δ₅**: crack tip opening displacement over a 5 mm gauge length
- **Δδ₅**: increment of δ₅ associated with stable crack extension ΔΔa
- **λ**: loading ratio, Fx / Fy, for bi-axial testing cruciform specimens
- **W**: specimen width
- **C(T)**: compact specimen
- **M(T)**: middle crack tension specimen
- **CF, CFS**: cruciform specimen
- **DS**: double slant fracture mode
- **SS**: single slant fracture mode

1. INTRODUCTION

It is now commonplace that every effort has to be taken to save natural resources, such as fossil energy and raw materials. This is particularly true for transportation systems where masses have to be accelerated and decelerated and hence measures for saving those resources
can be very effective. Thus, reduction of structural mass is a key issue in the design of transportation structures. Among other measures, such as using lighter and stronger materials and applying new design principles, weight saving can be achieved by high exploitation of the actual structural mass. This in turn requires accurate methods for characterising the materials used and for assessing structural integrity.

As light-weight structures are mainly made of thin-walled materials, their failure is usually associated with large amounts of stable crack extension; large scale yielding conditions may also be present. In such cases the applicability of K- and J- based fracture mechanics concepts is limited. At present, work on the integrity of thin-walled structures is focussed on concepts which seem to be better suited for dealing with large amounts of crack extension. These concepts are based on the crack opening displacement, $\delta_5$, and the crack tip opening angle, CTOA.

Early theoretical work [1,2] demonstrated that for elastic-ideally plastic materials the strains at the tip of an extending crack are characterised by the crack tip opening angle, CTOA. It was shown by experimental work and finite element analyses [3] that after a short initiation phase the crack tip opening angle attains a steady state condition which means that cracks propagate with a nearly constant opening angle over a wide range of crack extension. This has stimulated the hope that CTOA can be used for an efficient characterization of large amounts of ductile crack extension in large structures. Meanwhile numerous experimental and numerical studies on applying CTOA fracture concepts in failure assessment have been undertaken during the last decade; for an overview see [4,5]. As a result, CTOA based fracture mechanics concepts have become mature, and two standard methods aimed at determining the critical CTOA, $\Psi_c$, for stable crack extension as well as the $\delta_5$-crack resistance curve, in particular for testing laboratory specimens with low out of plane constraint, are either already available (ASTM E 2472-06) [6] or in the final stage of development (ISO/FDIS 22889:2006) [7]. In order to achieve low constraint conditions, the standards require testing specimens which have a slender ligament. This is usually the case for specimens made from thin sheet material. More precisely, such low-constraint testing condition is realized in C(T)- and M(T)-specimens, if the condition
\[(W - a_0)/B \geq 4\] (1)

is met, where \(a_0\) is the fatigue pre-crack length, \(W\) the specimen width and \(B\) the specimen thickness.

For the determination of material specific critical CTOA-data, the draft standards offer various experimental methods e.g. optical imaging techniques, where the propagating crack tip is directly photographed on the specimen surface, or a fractographic method, where the fracture surface morphology is analysed using laser scanning techniques. In the standards, thoughts are also given to deriving CTOA-data from \(\delta_5\) clip gauge measurements picked up on the side surface of the specimen. Compared to optical methods such clip gauge technique would have the practical advantage of easy application, however, practical experience is still very limited [8].

In order to validate some of the methods described in the draft standards, this paper provides comprehensive a data set on stable crack extension in a thin-walled aluminium sheet material, characterized by the \(\delta_5\)-R-curve as well as by CTOA. Other objectives of the work described in this paper are a study into possible specimen size and geometry effects on R-curves and CTOA, and the comparison of the optical and \(\delta_5\) methods for the experimental determination of the crack tip opening angle. To this end, crack extension experiments were performed on various specimen geometries representing different in-plane constraint conditions. The results shown in this paper present a subset of a comprehensive research project reported in Ref. [9].

## 2. METHODS

### 2.1 Optical CTOA Determination

In this study, CTOA values were measured according to the methods detailed in the standards [5,6]. Pre-cracked laboratory specimens were quasi-statically loaded under displacement controlled conditions. For determining CTOA, the crosshead displacement of the testing machine was stopped, and the actual crack tip visible at the specimen’s side surface was photographed by using a light microscope combined with a digital camera.

Fig. 1 shows a typical micrograph of a crack in the Al 5083 sheet material. In order to achieve high quality micrographs, the side surfaces of the specimen were polished before the test. In addition, a pattern of fine equidistant lines on the side surface of the specimen allows
determination of the actual crack length and the amount of crack extension. By this technique, each test delivers a sequence of micrographs. For each micrograph, a CTOA_{opt} can then be graphically derived by the procedure illustrated in Fig. 1. Two points at the crack franks close to the crack tip serve as a reference for deriving a set of CTOA_{Li}-values associated with different base-lengths, \( L_i \). The CTOA_{opt}-value is then obtained by averaging the CTOA_{Li}-values according Eq.2. The CTOA_{opt}-related crack extension value can be derived from the line pattern also visible in each individual micrograph.

\[
CTOA_{opt} = \frac{1}{n} \sum_{i=1}^{n} CTOA_{Li}, n \geq 5
\]  

2.2 Determination of CTOA using \( \delta_5 \) measurement technique

During the last decades GKSS has developed a fracture mechanics concept based on the crack opening displacement (COD) \( \delta_5 \) \[10-17\]. In this concept a special clip gauge technique is used to measure COD \( \delta_5 \). Fig. 2 shows an example of its application: The clip gauge is mounted on the side surface of a C(T) specimen close to the pre-fatigue crack tip, over a gauge length of 5 mm defined by two hardening indentations located 2.5 mm above and below the pre-fatigue crack tip. This technique can be applied to a variety of specimen types e.g. SE(B)- M(T)- and cruciform specimens (CF-specimens) as well as to real engineering structures. During stable crack extension, \( \Delta a \), the \( \delta_5 \) clip gauge picks up the increase of the distance between the two hardening indentations, and thus an opening displacement. As a result, a \( \delta_5 \) crack resistance curve, \( \delta_5 = f(\Delta a) \), is obtained.

Following the idea of deriving meaningful crack tip opening angles by the \( \delta_5 \) measurement technique it is helpful to recall the deformation behaviour of the material at the very crack tip. Associated with stable crack extension, new crack flanks and hence, new crack tip opening displacements (CTOD) are continuously formed. With the assumption that the crack flanks of a moving crack tip form a triangle, a crack tip opening angle can be defined by the following simple estimate:

\[
CTOA = \frac{CTOD}{\Delta \Delta a} [\text{rad}]
\]  

In this equation, CTOD is the distance between two opposite points at the crack flanks behind the crack tip, see Figure 3. This CTOA definition is consistent with the procedure applied for
the determination of CTOA\textsubscript{opt}, see Fig. 1. Similar to the optical method a the crack tip opening angle can be defined by

$$CTOA_{\delta 5} = \Delta \delta_5 / \Delta \Delta a$$  \hspace{1cm} \text{[rad]} \hspace{1cm} (4)$$

In this equation, $\Delta \delta_5 / \Delta \Delta a$ represents the slope of the $\delta_5$ R-curve, see Figure 3. The validity of Eq.(4) has not yet been comprehensively investigated. Promising results based on a very limited set of experimental data are shown in Refs. [8]. Doubt as to the usefulness of Eq. (4) may arise since $\delta_5$ measures the crack opening at a fixed location, whereas CTOA\textsubscript{opt} measures near the moving crack tip. Therefore, the present paper provides additional results for this subject.

3. FRACTURE TESTS

The following test program was undertaken to validate the above described techniques.

Material

The material used in this study was a medium strength conventional 3 mm thick Al 5083 H321 rolled sheet which is widely used in transportation industries. Its chemical composition is listed in Table 1. The alloy contains large particles and elongated particle clusters, see Fig. 4. As seen at high magnification many of the particles are fractured due to the rolling process. In the literature [18] it is reported that most of the particles are brittle (Fe,Mn)$_3$SiAl$_{12}$- and MnAl$_6$- phases. The tensile properties derived from flat tensile specimens are summarized in Table 2. In all mechanical tests (tensile tests, fracture mechanics tests) a non-uniform load - deformation behaviour was observed for this material due to the Portevin-Le Chatelier – Effect. As an example, see the load drops in the stress-strain curves shown in Fig. 5.

Test pieces

The experimental test program covered specimens subjected to bending, tension and biaxial loading, realised by C(T)-, M(T)- and CF-specimens, all machined from a single batch of a rolled sheet material. In addition to the variation of specimen geometry, the test matrix includes also variations of the specimen in-plane dimensions in order to study size effects. The C(T)- and CF-specimens were equipped with guides to avoid buckling. The specimen is kept between two stiff steel plates. In order to minimise friction, thin Teflon foils were
inserted between the steel plates and the specimen surfaces. To enable monitoring of the growing crack tip during the test, the steel plates were equipped with narrow slots along the expected crack path. The dimensions and design of the CF-specimen are shown in Figure 6. The C(T)- and M(T)-specimen design was in agreement with the recommendations given in the draft standards.

Two C(T)-specimens were tested in TL-orientation whereas the remaining specimens were LT-oriented. In preparation of the fracture tests, all specimens were pre-cracked using a maximum $\Delta K$-value of about 10 MPam$^{1/2}$ and a load ratio of R= 0.1.

Tables 3a,b,c summarises the fracture tests performed including several technical details.

4. RESULTS AND DISCUSSION

4.1 Crack path development

Although preparation, instrumentation and loading conditions of all test specimens were kept identical, the specimens developed different types of crack path during stable crack extension. In a few specimens a “roof-shaped“, double-slant (DS) fracture surface developed immediately ahead of the pre-fatigue crack tip. The thus formed crack path includes an angle of 35° with the direction of the pre-fatigue crack. With increasing stable crack extension, the DS-cracks change to single-slant (SS) fracture surface, where the crack grows parallel to the pre-fatigue crack. A schematic and a macrograph demonstrate this behavior, see Fig. 7. In about 30% of the tests such DS-cracks have been observed. In the draft standard these tests are regarded as “invalid” tests, it means that the test all results have to be discarded. Therefore, in cases where a DS-crack was observed, the test data were either completely eliminated form this study or CTOA-data were only derived in the regime where the DS-crack had changed to a SS-crack.

During stable crack extension, only moderate crack front tunneling was observed in all types of specimen, see Fig. 8. This justifies the method of deriving stable crack extension data, $\Delta a$, using the line pattern marked of the specimen’s side surface. The fracture surface is not even but shows a wavy profile. It is caused by non-uniform stable crack propagation during the test associated with the non-uniform plastic deformation of the material also seen in case of the tensile tests data in Fig. 5.
4.2 CTOA determined by the optical method

The aim of fracture mechanics tests was to determine $\text{CTOA}_{\text{opt}}$ and $\text{CTOA}_{\delta 5}$ for stably extending cracks, which initiate at the fatigue pre-crack and then propagate throughout the entire specimen ligament. For a direct comparison between $\text{CTOA}_{\text{opt}}$ and $\text{CTOA}_{\delta 5}$, the $\delta_5$-data and the crack tip micrographs were taken simultaneously on each specimen. This was realized by picking up the $\delta_5$-data at one side-surface and taking the crack tip micrographs on the opposite side of the specimen.

In order to determine $\text{CTOA}_{\text{opt}}$ the draft standards recommend deriving the crack tip opening angle within 1 mm behind the actual crack tip. For a reliable practical application of the camera technique as well as for a reduction of the CTOA data scatter [8], the $\text{CTOA}_{\text{opt}}$-values shown in this paper were determined within 1.5 mm behind the crack tip. Each individual $\text{CTOA}_{\text{opt}}$-value shown in the diagrams below represents a single micrograph analyzed by the procedure shown in Fig. 1 and Eq. 2.

In order to investigate possible specimen size and geometry effects, the $\text{CTOA}_{\text{opt}}$-data obtained on all specimen types were plotted versus stable crack extension, $\Delta a$. For a detailed visual analysis, the CTOA-data are presented at different $\Delta a$-scales, see Figs. 9a,b,c. All specimens shown in these diagrams exhibited a single slant fracture mode over the entire regime of stable crack extension, except the large C(T)-specimen indicated by (1.2.4). This specimen developed a double slant crack at the beginning of crack extension and then changed to a single slant mode. However, for this large C(T)-specimen all $\text{CTOA}_{\text{opt}}$-data were determined only within the single slant range. Due to the design of the anti-buckling guides no crack tip micrographs could be taken within the range of $100 \text{mm} < \Delta a < 180 \text{mm}$. This explains the missing $\text{CTOA}_{\text{opt}}$-data point for specimen (1.2.4) within that regime, see Figure 9a.

A close examination of the data points in Figs. 9a,b,c allows drawing several conclusions concerning the specimen size and geometry effects on the $\text{CTOA}_{\text{opt}}$ versus $\Delta a$ relation:

**Crack extension range $\Delta a < 5 \text{mm}$**

Within the first 3 mm of stable crack extension, CTOA decreases sharply for all types of specimens. With further crack extension, the CTOA approaches a lower bound of about 5°. The CTOA of C(T)-specimens seem to touch this lower bound at slightly smaller $\Delta a$ values as compared to M(T)-specimens, see Figs. 9b and 9c.
Large crack extension:
Testing under displacement controlled condition, usually allows driving the crack stably through the entire specimen ligament. According to the draft standards, size and geometry effects on CTOA are to be expected in cases where the propagating crack tip approaches the back face of the specimen. This upper limit of crack extension is quantified by:

\[
\Delta a_{\text{max, CTOA}} = (W-a_0) - 4B
\]  

(5)

The data in Figure 10 confirm the validity of Eq.(5) because in the range 5mm < \Delta a < \Delta a_{\text{max CTOA}}, the CTOA of all types of specimens (C(T)-, M(T)- and CF-specimen) scatters around a constant mean value of 5°. This conclusion is in particular supported by the data obtained from the large C(T)-specimen, which provided CTOA-values of 5° up to 200 mm of crack extension, see Fig. 9a.

Two examples demonstrate the importance of introducing the limit \(\Delta a_{\text{max CTOA}}\). In case of the small and large C(T)-specimens designated by (11,22) and (555,666), Eq. (4) yields \(\Delta a_{\text{max CTOA}}\)-values of 12 mm and 63 mm. For these specimens the diagrams exhibit a significant upswing of the CTOA=f(\Delta a) curve, when \(\Delta a\) exceeds the limit defined by Eq.(5), see Figs. 9b and 10.

From these results it follows that the resistance to stable crack extension of the material investigated is characterized by two distinct regions with significantly different CTOA-behavior. Following initiation of crack extension, CTOA_{\text{opt}} decreases strongly until it reaches steady state conditions characterized by a constant value, thus confirming the earlier findings mentioned in the introduction [3]. This crack propagation phase is terminated by \(\Delta a_{\text{max CTOA,\delta}}\) as defined by Eq.(5). The fact that the crack tip opening angle exhibits a constant value over a very wide range of crack extension and its geometry independence within the range of specimen geometries investigated confirm the usefulness of the optically determined crack tip opening angle, CTOA_{\text{opt}}, as determined by the methods outlined in the two standards, to characterize stable crack extension in a thin sheet material.

4.3 CTOA determined using the \(\delta_5\) clip gage technique

As already mentioned in the introduction, the two standards give also hints on determining CTOA from a \(\delta_5\) R-curve. In this section, CTOA values determined this way, CTOA_{\delta5}, will be compared with what is obtained from optical measurements.
The determination of $\text{CTOA}_{\delta_5}$ according to Eq. (4) requires the slope of the R-curve. This was done via the fitting procedure shown in Figure 11. In this procedure, for each R-curve data point $(\delta_{5i}, \Delta a_i)$ a linear regression fit over three neighboring data points located at $\Delta a_{i-1}$, $\Delta a_i$, $\Delta a_{i+1}$, was performed by weighting the middle point, $(\delta_{5i}; \Delta a_i)$ twice. The slope of the regression line, $\Delta \delta_5 / \Delta \Delta a$, was then used to calculate $\text{CTOA}_{\delta_5}$ associated with the amount of stable crack extension at $\Delta a = \Delta a_i$.

Because $\text{CTOA}_{\delta_5}$ is deduced from the $\delta_5$ R-curve it is worth considering the behavior the $\delta_5$ R-curve itself. The draft standards provide criteria for deriving size and geometry independent $\delta_5$ R-curves. They are defined as follows:

$$\Delta a_{\text{max C(T) R-curve}} = 0.25(W-a_o) \tag{6}$$
$$\Delta a_{\text{max M(T) R-curve}} = (W-a_o) - 4B \tag{7}$$

According to these criteria, approximately geometry and size independent $\delta_5$ R-curves can be measured on a specimen as long as stable crack extension, $\Delta a$, does not exceeded $\Delta a_{\text{max}}$. The application of the criterion in Eq.(6) to two R-curves obtained on C(T) specimens is shown in Figs. 12a and 12c. These curves were determined on specimens made of the same material and had the same size, however, the orientations were different. They exhibit a significant upswing beyond the limit $\Delta a_{\text{max CTR curve}}$. At stable crack extensions smaller than this limit, nearly identical $\delta_5$ R-curves are observed for M(T)- and C(T)-specimens, Fig. 12a. Although it is not explicitly demonstrated by examples, also in the case of M(T)-specimen, Eq. (7) can be applied to identify the specimen size and geometry independent section of M(T) R-curves [9,10].

Figure 12b shows R-curves of CF- and M(T)-specimens where DS-cracks associated with a $35^\circ$ crack path have been observed. In such case, a specific R-curve development is obtained, with an increase of the crack extension resistance as shown by the dashed lines in Figure 12b. Since the crack path in an actual structural component may be of the single slant mode a test with double slant mode will then overestimate the component’s crack resistance. The analysis in Ref [9] has show that $\text{CTOA}_{\text{opt}}$ associated with DS-cracks is also larger compared to that observed for single slant cracks. Therefore, in order to avoid overestimation of crack resistance in components, the standards classify such tests as “invalid tests”. Note, in the present paper $\text{CTOA}_{\text{opt}}$-data associated with DS-cracks have been discarded and are hence not shown here.
In order to investigate the meaning of CTOA$_{\delta 5}$, those sections of the R-curves in Figure 12 meeting the requirements of Eqs.(6) and (7) have been analyzed as outlined in Figure 11. The results are presented in Figs. 13a,b,c, by plotting the difference between CTOA$_{\delta 5}$ and CTOA$_{opt}$ as a function of stable crack extension. It is seen that for all types of specimens, the differences between CTOA$_{\delta 5}$ and CTOA$_{opt}$ vanish as long as stable crack extension remains smaller than about 4 mm. With increasing crack extension, the curves associated with M(T)- and CF-specimens exhibit a continuous deviation between both definitions of CTOA, see Figs. 13a and 13b. The reason for this behavior is due to the gradual decrease of the slope of the R-curves of M(T) and CF specimens, and hence the values generated according to Eq.(3). Therefore, a derivation of CTOA values from $\delta 5$ R-curves is conservative because it underestimates the true crack resistance of the material tested but since this underestimation is quite substantial it can not be recommended as a useful parameter. The optical CTOA-value is realistically considered the true one.

The situation is different when examining the results obtained on the 50 and 100 mm wide C(T) specimens: The two types of crack tip opening angle CTOA$_{opt}$ and CTOA$_{\delta 5}$ match well over the entire $\Delta a$ regime, see Figs. 13c and 13d. However, this is not the case for the large W=1000mm C(T)-specimen. In that specimen, CTOA$_{\delta 5}$ is considerably smaller than the optical values, see Fig. 13d. No reasonable explanation for this behavior can be given, other than that narrow and wide C(T)- specimens may have different deformation behavior.

These observations show that CTOA$_{\delta 5}$ and CTOA$_{opt}$ behave differently during stable crack propagation. While CTOA$_{opt}$ is nearly constant and numerically identical over large amounts of crack extension for all types and sizes of specimens investigated, the CTOA$_{\delta 5}$ quantity has the tendency to drop more or less significantly during crack extension, depending on which specimen size and geometry is considered.

The observation and results outlined above indicate that good agreement between CTOA$_{opt}$ and CTOA$_{\delta 5}$ is obtained in all types of specimens as long as the $\delta 5$ clip gauge is located sufficiently near to the growing stable crack tip. With increasing crack extension the correlation between of $\delta 5$ clip gauge readings and crack tip stress strain fields vanishes whereas the macroscopic deformation property of the specimens is increasingly affecting the clip gauge readings.

This limited consistency between both methods for CTOA determination does not imply that the $\delta 5$ R-curve is less suited for material characterization than optical CTOA. The diagrams in
this paper as well as in numerous other publications, e.g. [9-17], demonstrate that this $\delta_5$ R-curve technique is sufficiently used for both material characterization and structural assessment.

5. SUMMARY AND CONCLUSIONS

The experimental investigation of the behaviour of the crack tip opening angle in three specimen configurations made of a thin aluminium sheet, representing different loading conditions and hence different in-plane constraints, was aimed at validating core topics of recent standardisation activities within ASTM and ISO. These activities deal with testing specimens under low constraint and are close to approval by the respective committees. From the investigation reported in this communication, the following conclusions emerge:

- The requirements imposed by standards on the quantities to be determined, where confirmed by the experiments.
- In the three specimen geometries investigated, the $\text{CTOA}_{\text{opt}}$ as determined by optical microscopy of the near-tip area is constant after a short transition range and independent on the specimen geometry and size.
- This supports the view that CTOA is a useful material parameter for characterizing the fracture mechanics properties of a material and hence for structural assessment.
- Within the validity range specified by the two standards, the $\delta_5$ R-curves are also geometry independent.
- In some cases, the crack path formed a double slant fracture surface with a crack path deviation of $35^\circ$. The draft standard methods regard these results as invalid. The R-curves show the reason for this: Double slant fracture results in substantially higher crack resistance which may overestimate the resistance present in a structural component and thus lead to non-conservative assessments.
- At the initiation of stable crack extension $\text{CTOA}_{\delta_5}$ is equal that of $\text{CTOA}_{\text{opt}}$ within the bounds of about $\pm 1^\circ$. With increasing crack extension the correlation between the $\delta_5$ clip gauge readings and crack tip stress strain fields vanishes and depending on the specimen geometry and size $\text{CTOA}_{\delta_5}$ may more or less significantly deviate from that of $\text{CTOA}_{\text{opt}}$. 

- In the present investigation, the alternative way for determining CTOA from $\delta_5$ R-curves as recommended by the draft standards, could only be verified in case of C(T) specimens with widths between 50 mm and 150 mm.

### Table 1: Chemical composition of Al5083

<table>
<thead>
<tr>
<th>Element</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Cr</th>
<th>Ti</th>
<th>Zn</th>
<th>Cu</th>
<th>Ni</th>
<th>Al</th>
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</thead>
<tbody>
<tr>
<td>weight%</td>
<td>4.64</td>
<td>0.59</td>
<td>0.26</td>
<td>0.15</td>
<td>0.084</td>
<td>0.019</td>
<td>0.012</td>
<td>0.006</td>
<td>0.004</td>
<td>rest</td>
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</tbody>
</table>

### Table 2: Tensile properties of Al5083 H321 sheet

<table>
<thead>
<tr>
<th>Specimen orientation</th>
<th>$R_{p02}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>$A_5$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° (L)</td>
<td>241</td>
<td>345</td>
<td>12</td>
</tr>
<tr>
<td>22.5°</td>
<td>233</td>
<td>340</td>
<td>14</td>
</tr>
<tr>
<td>45°</td>
<td>225</td>
<td>329</td>
<td>16</td>
</tr>
<tr>
<td>67.5°</td>
<td>227</td>
<td>331</td>
<td>16</td>
</tr>
<tr>
<td>90° (T)</td>
<td>235</td>
<td>337</td>
<td>16</td>
</tr>
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Table 3a:
Test matrix of middle crack tension specimens, M(T)

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<tr>
<th>Test of M(T).</th>
<th>2W [mm]</th>
<th>CTOA&lt;sub&gt;opt&lt;/sub&gt;</th>
<th>CTOA&lt;sub&gt;85&lt;/sub&gt;</th>
<th>Type of crack</th>
<th>a&lt;sub&gt;0&lt;/sub&gt;/W</th>
<th>anti-buck.</th>
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<tr>
<td>2.1.26</td>
<td>100</td>
<td>X</td>
<td>X</td>
<td></td>
<td>0.3</td>
<td>no</td>
</tr>
<tr>
<td>2.1.27</td>
<td>100</td>
<td>X</td>
<td>X</td>
<td>1 DS-crack</td>
<td>0.3</td>
<td>no</td>
</tr>
<tr>
<td>2.1.8</td>
<td>300</td>
<td>X</td>
<td>X</td>
<td></td>
<td>0.2</td>
<td>no</td>
</tr>
<tr>
<td>1.1.2</td>
<td>300</td>
<td></td>
<td></td>
<td>2 DS-cracks</td>
<td>0.2</td>
<td>yes</td>
</tr>
<tr>
<td>2.1.11</td>
<td>300</td>
<td></td>
<td></td>
<td>1 DS-crack</td>
<td>0.2</td>
<td>no</td>
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<tr>
<td>1.1.3</td>
<td>300</td>
<td>X</td>
<td>X</td>
<td></td>
<td>0.2</td>
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</table>
**Table 3b:**
Test matrix of compact specimens, C(T)

<table>
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<tr>
<th>Test of C(T)</th>
<th>W [mm]</th>
<th>CTOA\text{opt}</th>
<th>CTOA\delta_5</th>
<th>Type of crack</th>
<th>Orientation, all anti-bucking</th>
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</thead>
<tbody>
<tr>
<td>11</td>
<td>50</td>
<td>X</td>
<td>X</td>
<td></td>
<td>LT</td>
</tr>
<tr>
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<td>50</td>
<td>X</td>
<td>X</td>
<td></td>
<td>LT</td>
</tr>
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<td>77</td>
<td>150</td>
<td>X</td>
<td>X</td>
<td></td>
<td>LT</td>
</tr>
<tr>
<td>555</td>
<td>150</td>
<td>X</td>
<td>X</td>
<td></td>
<td>TL</td>
</tr>
<tr>
<td>666</td>
<td>150</td>
<td>X</td>
<td>X</td>
<td></td>
<td>TL</td>
</tr>
<tr>
<td>1.2.4</td>
<td>1000</td>
<td>X</td>
<td>X</td>
<td>ds-crack</td>
<td>LT</td>
</tr>
<tr>
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<td>1000</td>
<td>X</td>
<td>X</td>
<td></td>
<td>LT</td>
</tr>
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</table>

**Table 3c:**
Test matrix of cruciform specimens, (CF)

<table>
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<tr>
<th>Test of (a_0/W=0.2)</th>
<th>Loading-ratio, (\lambda)</th>
<th>CTOA\text{opt}</th>
<th>CTOA\delta_5</th>
<th>Type of crack</th>
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<td>X</td>
<td>2 DS-cracks</td>
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<tr>
<td>3.1.5</td>
<td>0,5</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4.1.4</td>
<td>0,5</td>
<td>X</td>
<td>X</td>
<td>1 DS-crack</td>
</tr>
<tr>
<td>3.1.6</td>
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<td>X</td>
<td>X</td>
<td>2 DS-cracks</td>
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<tr>
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<td>-0,5</td>
<td>X</td>
<td>X</td>
<td>2 DS-cracks</td>
</tr>
</tbody>
</table>
6. REFERENCES


FIGURES

Figure 1:
Micrograph showing the crack flanks behind a stable growing crack tip in Al5083 sheet material. Determination of $CTOA_{opt}$ by averaging the individual $CTOA_{Li}$-values distributed in the regime behind the crack tip.
Figure 2: Example of mounting the δ5-clip gauge near the pre-fatigue crack tip of a C(T)-specimen.
Figure 3:
Schematics of deriving a crack tip opening angle
a) by using the slope of $\delta_5$-R-curve,
   b) by measuring CTOD close to the propagating crack tip.
Figure 4:
Clusters of inclusions and grains elongated in rolling direction on polished and etched LT-plane
Figure 5:
Engineering stress-strain curves of the Al 5083 H321 sheet material. Load drops observed at strains larger than 3%.
Figure 6:
Design of the cruciform specimen.
Figure 7:
Types of crack path development:
  a) single slant (SS) fracture ahead of the pre-fatigue crack tip
  b) double slant (DS) fracture associated with crack path deviation ahead of the pre-fatigue crack.
Figure 8:
Typical fracture surface as observed for slant fracture.
Figure 9a,b,c:
CTOA_{opt} as functions of crack extension on three different $\Delta a$ scales.
CTOA<sub>opt</sub> increases significantly when stable crack extension exceeds the limit Δa<sub>max,CTOA</sub>.

**Figure 10:**
CTOA<sub>opt</sub> increases significantly when stable crack extension exceeds the limit Δa<sub>max,CTOA</sub>.
Figure 11:
Method of fitting the R-curve data points for the determination of CTOA$_{85}$.
Figure 12a:
Influence of specimen geometry and size on $\delta_3$ R-curves.
$\Delta a_{\text{max},C(T)} = 0.25(W-a_o)$ limit for size independent R-curves according to the draft standards.
Figure 12b:
Influence of crack path development on R-curves of CF- and M(T)-specimens. (Full and dashed lines are associated with double-slant cracks, Symbols are associated single-slant cracks).
Figure 12c:
Example of identifying the geometry and size independent section of C(T)-specimen R-curves using the criteria $\Delta a_{\text{max}} \text{ C(T) R-curve} = 0.25 (W-a_0)$. 

$\delta_5, \text{ mm}$

$\Delta a, \text{ mm}$

$0.25(W-a_0)$

AI 5083, W=150mm 
$a_0/W=0.5, B=3\text{mm}$

- C(T) LT,(77)
- 2C(T) TL,(555,666)
Figure 13a:
Influence of stable crack extension on the difference between \( \text{CTOA}_{85} \) and \( \text{CTOA}_{\text{opt}} \) observed for \( \text{M(T)} \)-specimens.
Figure 13b:
Influence of stable crack extension on the difference between $\text{CTOA}_{\delta5}$ and $\text{CTOA}_{\text{opt}}$ observed for cruciform specimens.
Figure 13c:
Influence of stable crack extension on the difference between CTOA₅₅ and CTOAᵦᵢᵦ observed for C(T)-specimens.
Figure 13d:
Influence of C(T) specimen size on the difference between CTOA_{55} and CTOA_{opt}. 