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**CHARACTERIZATION OF STABLE CRACK EXTENSION IN ALUMINIUM-
SHEET MATERIAL USING THE CRACK TIP OPENING ANGLE DETERMINED
OPTICALLY AND BY THE δ_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 δ_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 those derived by using the δ_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 δ_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
a_0	crack length after pre-cracking
Δa	amount of stable crack extension
$\Delta \Delta a$	increment of stable crack extension
$\Delta a_{\max, \text{CTOA}}$	limit for CTOA controlled crack extension
$\Delta a_{\max, \text{M(T)}, \text{R-curve}}$	limit for δ_5 controlled crack extension in M(T)-specimens
$\Delta a_{\max, \text{C(T)}, \text{R-curve}}$	limit for δ_5 controlled crack extension in C(T)-specimens
B	specimen thickness
CTOA	crack tip opening angle
CTOA_{opt}	crack tip opening angle derived microscopically
CTOA_{δ_5}	crack tip opening angle derived using the δ_5 clip gauge technique
CTOD	crack tip opening displacement measured between the crack flanks
δ_5	crack tip opening displacement over a 5 mm gauge length
$\Delta \delta_5$	increment of δ_5 associated with stable crack extension $\Delta \Delta a$
λ	loading ratio, F_x / F_y , 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, δ_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, Ψ_c , for stable crack extension as well as the δ_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

$$(W - a_0)/B \geq 4 \quad (1)$$

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 δ_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 δ_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 δ_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 flanks 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.

$$CTOA_{opt} = 1/n \sum_{i=1}^n CTOA_{Li}, n \geq 5 \quad (2)$$

2.2 Determination of CTOA using δ_5 measurement technique

During the last decades GKSS has developed a fracture mechanics concept based on the crack opening displacement (COD) δ_5 [10-17]. In this concept a special clip gauge technique is used to measure COD δ_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, Δa , the δ_5 clip gauge picks up the increase of the distance between the two hardening indentations, and thus an opening displacement. As a results, a δ_5 crack resistance curve, $\delta_5 = f(\Delta a)$, is obtained.

Following the idea of deriving meaningful crack tip opening angles by the δ_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:

$$CTOA = CTOD/\Delta a [\text{rad}] \quad (3)$$

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 $CTOA_{opt}$, see Fig. 1. Similar to the optical method a the crack tip opening angle can be defined by

$$CTOA_{\delta_5} = \Delta\delta_5 / \Delta\Delta a \quad [\text{rad}] \quad (4)$$

In this equation, $\Delta\delta_5 / \Delta\Delta a$ represents the slope of the δ_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 δ_5 measures the crack opening at a fixed location, whereas $CTOA_{opt}$ 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 $(Fe,Mn)_3SiAl_{12}$ - 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 ΔK -value of about $10 \text{ MPam}^{1/2}$ 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 from 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, Δa , 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 $CTOA_{opt}$ and $CTOA_{\delta_5}$ for stably extending cracks, which initiate at the fatigue pre-crack and then propagate throughout the entire specimen ligament. For a direct comparison between $CTOA_{opt}$ and $CTOA_{\delta_5}$, the δ_5 -data and the crack tip micrographs were taken simultaneously on each specimen. This was realized by picking up the δ_5 -data at one side-surface and taking the crack tip micrographs on the opposite side of the specimen.

In order to determine $CTOA_{opt}$ the draft standards recommend deriving the crack tip opening angle within 1mm 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 $CTOA_{opt}$ -values shown in this paper were determined within 1.5 mm behind the crack tip. Each individual $CTOA_{opt}$ -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 $CTOA_{opt}$ -data obtained on all specimen types were plotted versus stable crack extension, Δa . For a detailed visual analysis, the CTOA-data are presented at different Δa -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 $CTOA_{opt}$ -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 $CTOA_{opt}$ -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 $CTOA_{opt}$ versus Δa 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 Δa 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:

$$\Delta a_{\max, \text{CTOA}} = (W - a_0) - 4B \quad (5)$$

The data in Figure 10 confirm the validity of Eq.(5) because in the range $5\text{mm} < \Delta a < \Delta a_{\max\text{CTOA}}$, 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 $\Delta a_{\max\text{CTOA}}$. In case of the small and large C(T)-specimens designated by (11,22) and (555,666), Eq. (4) yields $\Delta a_{\max\text{CTOA}}$ -values of 12 mm and 63 mm. For these specimens the diagrams exhibit a significant upswing of the $\text{CTOA}=f(\Delta a)$ curve, when Δa 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_{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 $\Delta a_{\max\text{CTOA}}$ 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_{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 δ_5 clip gage technique

As already mentioned in the introduction, the two standards give also hints on determining CTOA from a δ_5 R-curve. In this section, CTOA values determined this way, CTOA_{δ_5} , will be compared with what is obtained from optical measurements.

The determination of $CTOA_{\delta_5}$ 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 Δa_{i-1} , Δa_i , Δa_{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 $CTOA_{\delta_5}$ associated with the amount of stable crack extension at $\Delta a = \Delta a_i$.

Because $CTOA_{\delta_5}$ is deduced from the δ_5 R-curve it is worth considering the behavior the δ_5 R-curve itself. The draft standards provide criteria for deriving size and geometry independent δ_5 R-curves. They are defined as follows:

$$\Delta a_{\max \text{ C(T) R-curve}} = 0.25(W - a_0) \quad (6)$$

$$\Delta a_{\max \text{ M(T) R-curve}} = (W - a_0) - 4B \quad (7)$$

According to these criteria, approximately geometry and size independent δ_5 R-curves can be measured on a specimen as long as stable crack extension, Δa , does not exceeded $\Delta a_{\max}$. 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 $\Delta a_{\max \text{ CTRcurve}}$. At stable crack extensions smaller than this limit, nearly identical δ_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° 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 $CTOA_{\text{opt}}$ 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 $CTOA_{\text{opt}}$ -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 δ_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 Δa regime, see Figs. 13c and 13d. However, this is not the case for the large $W=1000\text{mm}$ 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 δ_5 clip gauge is located sufficiently near to the growing stable crack tip. With increasing crack extension the correlation between of δ_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 δ_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 δ_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, were confirmed by the experiments.
- In the three specimen geometries investigated, the $CTOA_{opt}$ 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 δ_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° . 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 $CTOA_{\delta_5}$ is equal that of $CTOA_{opt}$ within the bounds of about $\pm 1^\circ$. With increasing crack extension the correlation between the δ_5 clip gauge readings and crack tip stress strain fields vanishes and depending on the specimen geometry and size $CTOA_{\delta_5}$ may more or less significantly deviate from that of $CTOA_{opt}$.

- In the present investigation, the alternative way for determining CTOA from δ_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

Element	Mg	Mn	Fe	Si	Cr	Ti	Zn	Cu	Ni	Al
weight%	4.64	0.59	0.26	0,15	0.084	0.019	0.012	0.006	0.004	rest

Table 2:

Tensile properties of Al5083 H321 sheet

Specimen orientation	R_{p02} [MPa]	R_m [MPa]	A_5 %
0° (L)	241	345	12
22,5°	233	340	14
45°	225	329	16
67,5°	227	331	16
90° (T)	235	337	16

Table 3a:

Test matrix of middle crack tension specimens, M(T)

Test of M(T).	2W [mm]	CTOA_{opt}	CTOA₆₅	Type of crack	a₀/W	anti- buck.
2.1.26	100	X	X		0,3	no
2.1.27	100	X	X	1 DS-crack	0,3	no
2.1.8	300	X	X		0,2	no
1.1.2	300			2 DS-cracks	0,2	yes
2.1.11	300			1 DS-crack	0,2	no
1.1.3	300	X	X		0,2	yes

Table 3b:

Test matrix of compact specimens, C(T)

Test of C(T)	W [mm] all ($a_0/W=0.5$)	CTOA _{opt}	CTOA _{δ5}	Type of crack	Orientation, all anti-bucking
11	50	X	X		LT
22	50	X	X		LT
77	150	X	X		LT
555	150	X	X		TL
666	150	X	X		TL
1.2.4	1000	X	X	DS-crack	LT
1.2.5	1000	X	X		LT

Table 3c:

Test matrix of cruciform specimens, (CF)

Test of $a_0/W=0.2$	Loading- ratio, λ	CTOA _{opt}	CTOA _{δ5}	Type of crack
3.1.2	1,0	X	X	2 DS-cracks
3.1.5	0,5	X	X	
4.1.4	0,5	X	X	1 DS-crack
3.1.6	-0,5	X	X	2 DS-cracks
3.1.1	-0,5	X	X	2 DS-cracks

6. REFERENCES

- [1] Chitaley, A.D. McClintock, F.A., Journal of the Mechanics and Physics of Solids, 19, 1971, pp. 147-163.
- [2] Rice, J.R., Mechanics and mechanism of Crack Growth (Proceedings, Conference at Cambridge, England, M.J. May, Ed., British Steel Corporation Physical Metallurgy Centre Publication, 1975, pp. 14-39.
- [3] Kanninen, M. F., Rybicki, E. F., Stonesifer, R. B., Broek, D., Rosenfield, A. R., Marschall, C. W., Hahn, G. T., Elastic-Plastic Fracture Mechanics for Two-Dimensional Stable Crack Growth and Instability Problems, Elastic-Plastic Fracture, ASTM STP 668, 1979, pp. 121-150.
- [4] Newman, J. C., Shivakumar, K. N., McCabe, D. E., Finite Element Fracture Simulation of A533B Steel Sheet Specimens, Defect Assessment in Components - Fundamentals and Applications,ESIS/EGF9, Mechanical Engineering Publications, London, 1991, pp. 117-126.
- [5] Newman Jr., J. C., James, M. A., Zerbst, U., A review of the CTOA/CTOD fracture criterion, Engineering Fracture Mechanics, Vol. 70, Iss. 3-4, 2003, pp. 371-385.
- [6] ISO/FDIS 22889:2006, Metallic materials - Method of test for the determination of resistance to stable crack extension using specimens of low constraint, 2006.
- [7] ASTM E 2472-06: Standard Test Method for Determination of Resistance to Stable Crack Extension under Low Constraint Conditions, Annual Book of ASTM Standards, ASTM International, West Conshohocken, Vol.03.01, 2007.
- [8] Heerens, J., Schödel, M., On the determination of crack tip opening angle, CTOA, using light microscopy and δ_5 measurement technique, Engineering Fracture Mechanics, 70, 2003, pp.417-426.

- 9] Schödel, M., Bruchmechanische Untersuchungen der Rissöffnung bei stabilem Risswachstum in dünnen Blechen aus Al 5083, GKSS-Report 2006/6, 2006.

- [10] Hellmann, D, Schwalbe, K.-H., Geometry and Size Effects on J-R and δ -R Curves under Plane Stress Conditions, Fracture mechanics: 15. Symposium, ASTM STP 833, R.J. Sanford, Ed., American Society for Testing Materials, Philadelphia, 1984, pp. 577-605.

- [11] Schwalbe, K.-H., Cornec A., Heerens, J, The engineering Treatment Model (ETM)-a Simple Method for Estimating the Driving Force under Elastic-Plastic and Plane Stress Conditions; Defect Assessment in Components – Fundamentals and Application, ESIS/EGF9, J.G. Blauel and K.H. Schwalbe), Eds., Mechanical Engineering Publications, London, 1991, pp. 1111-1124.

- [12] Application of the Engineering Treatment Model to the Prediction of the Behaviour of a circumferentially Cracked Pipe; Defect Assessment in Components – Fundamentals and Application, ESIS/EGF9, J.G. Blauel and K.-H. Schwalbe, Eds., Mechanical Engineering Publications, London, 1991, pp. 1125-1133.

- [13] Heerens J, Schwalbe, K.-H., Nix C.; Influence of Specimen Size on J-, Jm-, and D5- R Curves for Side –Grooved Compact–Tension Specimens, Constraint Effects in Fracture, ASTM STP 1171, E.M. Hackett, K.-H. Schwalbe and R. H. Dodds, Eds., American Society for Testing Materials, Philadelphia, 1993, pp. 429-472.

- [14] Schwalbe, K.-H., Heerens, J., R-Curve Testing and its Relevance to Structural Assessment, Fatigue & Fracture of Engineering Materials & Structures, Vol. 21, 1998, pp. 1259-1271.

- [15] Schwalbe, K.-H., Zerbst, U., Brocks, W., Cornec, A., Heerens, J. and Amstutz, H., The ETM-Method for Assessing the Significance of Crack-Like Defects in Engineering Structures, Fatigue and Fracture of Engineering Materials & Structures, 21, 1998, pp. 1215-1231.

- [16] Nikishkov G., Heerens, J., Schwalbe, K.-H., Transformation of CTOD d5 to CTOD BS and J-Integral for 3PB- and C(T)-Specimens, Engineering Fracture Mechanics, 63, 1999, pp. 573-589.
- [17] Schwalbe, K.-H., Zerbst U., The Engineering Treatment Model, International Journal of pressure Vessel and Piping, 77, 2000, pp. 905-818.
- [18] ASM Speciality Handbook, Aluminium and Aluminium Alloys, Edited by J.R. Davis, Davis & Associates, Second Printing, 1994.

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 $\delta 5$ -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 δ_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 Δa scales.

Figure 10:

CTOA_{opt} increases significantly when stable crack extension exceeds the limit Δa_{max,CTOA}.

Figure 11:

Method of fitting the R-curve data points for the determination of CTOA_{δ_5} .

Figure 12a:

Influence of specimen geometry and size on δ_5 R-curves.

$\Delta a_{\max C(T)} = 0,25(W-a_0)$ 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 $\Delta a_{\max \text{ C(T) R-curve}} = 0.25 (W-a_0)$.

Figure 13a:

Influence of stable crack extension on the difference between $CTOA_{\delta 5}$ and $CTOA_{opt}$ observed for M(T)-specimens.

Figure 13b:

Influence of stable crack extension on the difference between $CTOA_{\delta 5}$ and $CTOA_{opt}$ observed for cruciform specimens.

Figure 13c:

Influence of stable crack extension on the difference between $CTOA_{\delta 5}$ and $CTOA_{opt}$ observed for C(T)-specimens.

Figure 13d:

Influence of C(T) specimen size on the difference between $CTOA_{\delta 5}$ and $CTOA_{opt}$.