Utilising COD_{max} as an Indirect Fatigue Crack Length Measurement Parameter for M(T) Specimens of an Airframe Aluminium Alloy AA6056

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Accuracy of indirect fatigue crack length measurement by potential drop method or by compliance technique may be affected at low load ratio due to fracture surface contact, crack closure or mixed mode fracture. As an alternative, the maximum value of crack opening displacement, COD_{max}, from a clip gauge was utilized. Middle crack tension M(T) specimens were used to obtain conservative data at a low load ratio (R = 0.1). Thin sheet specimens (B = 3.2 mm) with different widths (100 mm ≤ W ≤ 400 mm) of AA6056-T4 were investigated in the mid-regime (Paris regime), which is of interest for damage tolerance analysis. The use of COD_{max} is found to provide crack lengths equivalent to those measured optically. Hence, the method is very suitable for indirect crack length measurement. Furthermore, small width specimens provided data equivalent to large width specimens. Insofar, the size effect is found to be absent, and fatigue crack propagation data can be acquired on small width specimens when material availability is limited.

Accuracy of crack length measurement is found to be one of the primary sources of the data variability in fatigue crack propagation [1]. Since this earliest round robin, various indirect crack length measurement techniques have been studied in detail [2-4]. Now, the direct current potential difference (DCPD), the alternating current potential difference (ACPD) and the compliance turn out to be the most commonly used methods, and compact tension, C(T), specimens to be the first choice among the experimentalists. Compared to middle crack tension M(T) specimens, C(T) specimens do offer some experimental advantages. To mention a few, the material required is less, the machine capacity can be low and for initial calibration only two crack tips, against four in a M(T) specimen, need to be monitored on the surface. There is also an essential difference in the relative change in the ΔK level with the crack length, which is exponential for C(T) specimens, but linear for M(T) specimens as shown in Figure 1 for the equivalent specimen width. Thus, indirect crack length measurement would be more difficult for M(T) specimens than for C(T) specimens when the change in a given output signal (which should be dependent on the ΔK level) is weaker.

Although the fatigue crack propagation test has been standardized [5], questions about validity of data acquired may turn up due to various reasons. For example, at low load ratios when surfaces contact, the potential drop method is difficult to use. Also, the crack closure level is affected by the measurement technique [6]. When crack closure occurs, the accuracy of compliance measurement would be reduced. For crack length by compliance, correction factors are required which are dependent on many factors such as material, specimen size or load range [7]. This would limit the accuracy of data acquired. Moreover, specimen geometry can affect a fatigue crack propagation curve such that compared to C(T) specimens, M(T) specimens provide more conservative data [8-13].

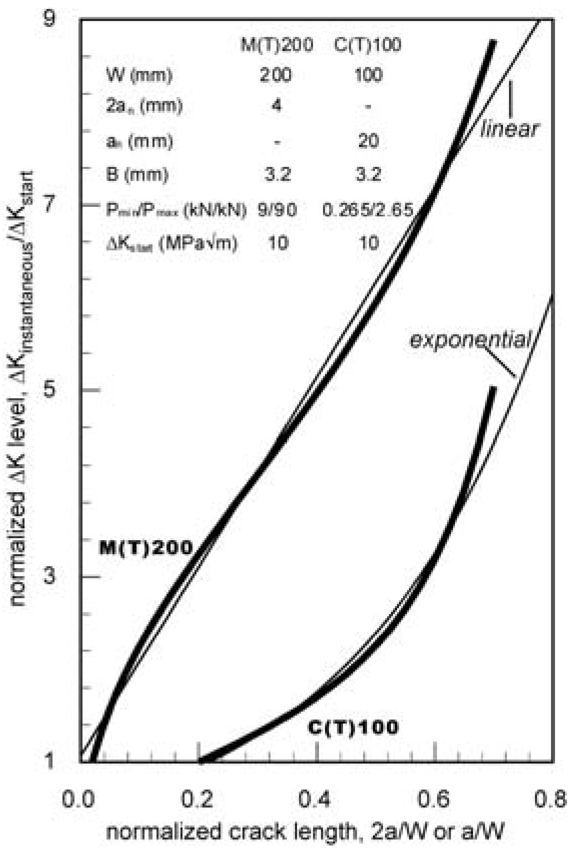

Figure 1. Difference in the relative ΔK level increase in a M(T)200 specimen and its half width equivalent C(T)100 specimen, note also that for the same ΔK starting level, the maximum load, hence the machine capacity required, is much higher for the M(T) specimen

When large width specimens are not available, small width specimens have to be tested at different ΔK starting levels, ΔK_{start}, to obtain overlapping data over a ΔK range. In such a case, however, a specimen size effect may be introduced. As the crack length and the ΔK value increase, the mode of propagation changes either partly or fully from tensile into shear, (i. e. mode I into II) [14].

The stress state may also change from plane strain to plane stress. If in addition to the fatigue mode (striations) ductile tearing occurs (e. g. dimples), crack propagation is accelerated and the slope m shall increase [15, 16].

Very early evidence by Paris et al. [17] has shown that irrespective of various test parameters fatigue crack propagation data from M(T) specimens of Al-alloys fall in a band. However, since the scatter band is broad, particularly for AA2024-T3, here the size effect cannot be excluded completely. We did not find any conclusive evidence on possible effect(s) of specimen width on fatigue crack propagation of M(T) specimens or recommendations in this context in the literature [18] which provides the largest single source laboratory data on aerospace Al-alloys. Small width specimens have been used in the literature [19, 20], but how these fatigue crack propagation data correlate with those of large width specimens has not been commented. Thus, questions on validity and equivalency of data due to the size effect cannot be excluded when variations in the fracture mode [14-16] are likely to occur.

We became involved in such a situation at a stage as new airframe Al-alloys for laser beam welding (fusion process) and friction stir welding (solid state process) were just introduced. Since the material available was limited at that time, C(T) specimens were the first choice. However, conservative data than possible on C(T) specimens [8-13] were required and were to be acquired on M(T) specimens and at a low load ratio (R = 0.1). The topics turned up were possibility of the size effect (specifically, specimen width) and the method to be used for the indirect crack length measurement.

Apart from problems related to surface contact, our trials with DCPD were not so successful due to signal variations observed even on notches (without cracks) and on non-propagating cracks probably due to temperature variations, although polarity was reversed, and the measurement time was kept short. The in-house developed ACPD [21] was very stable against temperature variations, but the potential difference signal was found to be weak, since aluminium does not exhibit a pronounced skin effect at the AC current frequencies used (≤ 8 kHz).

The authors' experience with compliance as an indirect crack length measurement technique was not so positive at slow propagation rates or when crack closure occurred [22, 23]. Therefore, following Sullivan and Crooker [24], we tried the maximum crack opening displacement value COD_{max} from a displacement gauge as a correlating parameter for the indirect crack length measurement. This method is found to be very suitable for C(T) specimens [13]. Here its suitability is verified for M(T) specimens of the base material. Thereby, whether small width specimens provide data equivalent to large width specimens (i. e. specimen width effect) is scrutinized in the mid-regime (Paris regime), which is of interest for damage tolerance analysis.

Experimental Procedure

The alloy AA6056 [25] is a newly developed Al-Mg-Si-Cu alloy that can be precipitation hardened to different strength levels. In contrast to AA2024 this alloy can be laser beam welded and has become attractive for aircraft industries for cost and weight saving [26].

The present heat was a new generation of AA6056 investigated previously [27]. The material was received in the T4 temper (hardened by GP zones) and had average tensile properties: yield strength $R_{p0.2}$ = 235 MPa, tensile strength R_m = 345 MPa and elongation A = 27 %, and was comparable in the longitudinal and the transverse directions. Insofar, regarding deformation, the material was nearly isotropic. The grains were partially recrystallised and had a pancaked shape with so long axis in the rolling direction. As to the fatigue crack propagation characteristics [27], the material is found to exhibit a higher resistance in the T4 temper (underaged) than in the T6 temper (peak-aged). Thus, any effect related to the specimen width should be detected more easily in the T4 temper as a change in the fatigue crack propagation pattern and the extent of scatter. For this reason the base material specimens were tested in the T4 temper.

All M(T) specimens were extracted by water jet cutting from a large single sheet (2500 × 1250 × 3.2 mm³) in the T-L direction so that the crack was to propagate along the rolling direction. The specimen width was varied from 100 mm to 400 mm, and is used for specimen identification, e. g. M(T)200 refers to a specimen with a width W of 200 mm.

The test specimens are shown in Figure 2. The smallest specimen, M(T)100, requires only about one-tenth of the material required for M(T)400 and in this respect Figure 2 is self-explanatory. The clamping length at top and bottom was 60 mm each for all specimens. The initial notch consisted of a central bore (1 mm ≤ ∅ ≤ 2 mm) and a slit on either side introduced by the electric discharge machining. So as to get more data, the notch was kept very short ($0.019 \leq 2a_n/W \leq 0.020$), and was shorter by a factor of ten than that recommended for compliance measurements ($2a_n/W \geq 0.20$) [5].

The specimens were fixed by clamping and tested without using anti-buckling guides. Care was taken to verify the axiality and that there was no bending. Different servo-hydraulic machines of appropriate capacity, 100 kN, 160 kN and 400 kN, were used and operated in the peak-load controlled sine wave mode. To obtain COD_{max} values, a displacement gauge was mounted in the centre of the specimen using knife-edges glued symmetrically and parallel to the notch as shown in Figure 3. The gauge was calibrated using the machine internal amplifier (1 mm ≡ 10 V). The load (P_{max} and P_{min}) and the displacement (COD_{max} and COD_{min}) signals were recorded along with the number of cycles and the time using a commercial digital data acquisition program (DASYLab) at an interval of 20 mV increase in COD_{max}. Thus, initially, as the crack propagated slowly, less data were obtained than towards the end of test as ΔK_c value ($K_{max} \rightarrow K_{Ic}$) was approached and COD_{max} changed substantially. Crack length was also monitored optically. In a reference test, the crack length was obtained only optically at a frequency f = 25 Hz while halting the test. In all other tests, optical method was used as a control and for the calibration. The test frequency was kept low (5 Hz ≤ f ≤ 10 Hz), since it was easier to observe the crack and to take readings without halting the test.

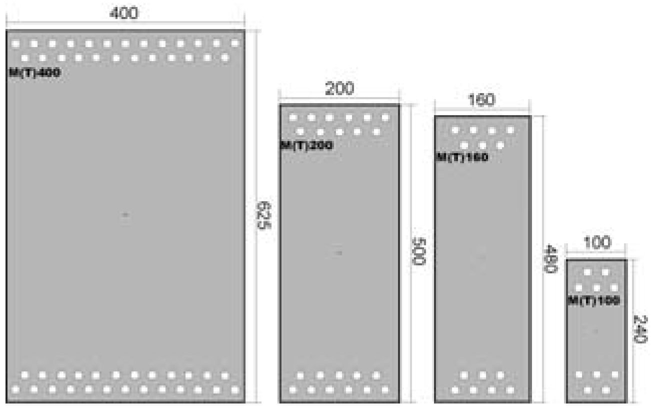

Figure 2. Dimensions of the specimens investigated (same scale for all drawings)

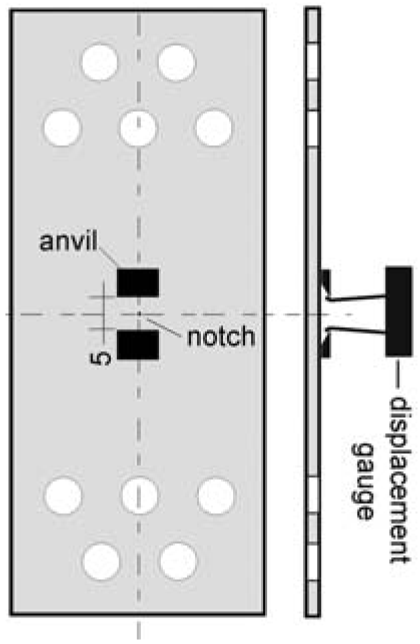

Figure 3. Location of the displacement gauge used for obtaining the COD_{max}-signal (not to scale)

During the test, data acquired manually were the instantaneous number of cycles, the corresponding COD_{max} value and the optical crack length. The reading interval was kept short (0.2 mm ≤ Δa ≤ 1 mm). After the test, with these manual data a calibration curve was obtained between COD_{max} and the optical crack length. Using the curve then fitted, all COD_{max} values recorded digitally were converted to crack lengths, from which da/dN and ΔK values were calculated. Except for averaging the data over ten points, additional data reduction or smoothing was not undertaken. So as to obtain overlapping crack propagation data, two ΔK starting levels were used for a given width; low ΔK (3 MPa√m ≤ ΔK_{start} ≤ 6 MPa√m) and high ΔK (7 MPa√m ≤ ΔK_{start} ≤ 10 MPa√m). Load ratio was 0.1 for all tests, (and should yield large variability in crack propagation). Unless stated otherwise, the tests were carried out mostly in close compliance with the ASTM standard [5].

Results and Discussion

Fracture Mode Variation. When different ΔK_{start} values are used, the fracture mode variation [14] is to be expected. A typical example is shown in Figure 4. The lower the ΔK_{start} value, the longer was the crack length in mode I (tension/flat fracture) before mode II component (shear/slant fracture) increased with the increase in the crack length and the ΔK value. For the higher ΔK_{start} value, the mode I propagation was limited and the shear mode became more evident. Also, the unstable fracture occurred after a shorter crack length extension. This trend was observed in all specimens irrespective of the width.

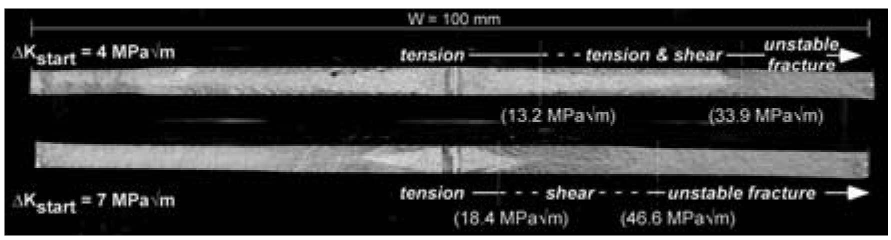

Figure 4. Fracture mode variation with the different ΔK starting levels in M(T)100 specimens

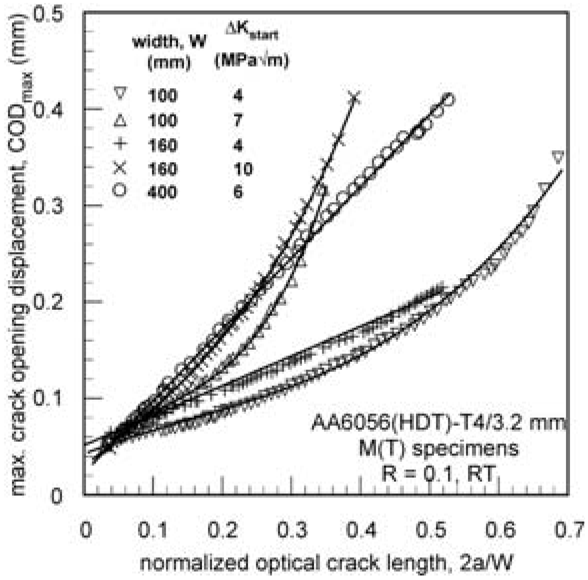

Figure 5. Development of COD_{max} value with the crack length and the ΔK starting value in different M(T) specimens

Markings on the fracture surface corresponding to crack front lag were absent (Figure 4). This indicates that the face-to-face crack propagation was nearly comparable, probably because the specimens were thin, the axiality was guaranteed, and the microstructure was also uniform.

In general, when the crack turns from the flat into the slant mode [14] and the state of strain changes (plane stress → plane stress), the acquisition of crack length, and the validity of crack propagation data may not be in favour of testing small width specimens. In the following, these aspects are examined on M(T) specimens with different widths.

Correlation between Direct and Indirect Crack Length Measurement. The variation of COD_{max} with the optical crack length measured manually is shown in Figure 5. The low ΔK_{start} test needed to be halted overnight. During such unattended runs the specimen was held at P_{mean}, and in some cases the COD_{max} signal was found to drop detectably (≤ 2 %), maybe due to noise, temperature variation or zero drift [22]. From our work on copper [23] we assume that this may be an effect related to back stresses from the retained damage in the plastic zone, which restrain the crack tip and decrease the opening. Fortunately, after restarting the test, the signal was picked-up again after a few hundreds of cycles. Therefore, corrections to COD_{max} signal such as readjustments, were not required.

The signal response was different for different specimens (Figure 5). Nonetheless, there was a certain systematic in the effect of specimen width and the ΔK_{start} value on the development of COD_{max}. As long as the crack propagated mostly in the tensile mode, the curve was nearly linear in M(T) 400, M(T) 160 and partly in M(T) 100 when tested at low ΔK_{start}. However, when the crack propagated in the mixed mode, as in M(T) 160 and M(T) 100 tested at high ΔK_{start} value, the curve shape changed and was fitted to polynomial of degree three. The curve fitting parameter R^2 had a value of 0.99 for all cases.

Using the fitting curve obtained (Figure 5), the COD_{max} values were converted to crack lengths. The correlation between the direct and the indirect crack length measurement is shown in Figure 6. In all specimens a nearly 1:1 correlation was observed, not only for small width (Figure 6a), but also for large width specimens (Figure 6b), and the resolution was comparable to that for the optical method. Thus, as for C(T) specimens [13], COD_{max} turns out to be a very suitable parameter also for the indirect fatigue crack length measurement of M(T) specimens.

It must also be pointed out that the variation of COD_{max} was dependent on the ΔK_{start} value and the specimen width, and that the shape of the given calibration curve was not unique (Figure 5). Therefore, it was necessary to calibrate each and every specimen. In contrast, for example, with DCPD the shape of the calibration curve (for saw-cut cracks) differs when a specimen geometry is changed [28], but not from specimen to specimen of a given geometry (in fracture mechanics tests). Thus, with a single calibration curve different specimens of a given geometry can be tested (at high load ratios). In this context, the COD_{max} method used is not so advantageous since optical reference data are required for every specimen. Insofar, since the method requires manual attendance (when video recording is unavailable), it is not so suitable for full automation. On the other hand, COD_{max} variations already encompass individual features such as deflection, deviation, face-to-face differences or branching of the crack.

From Figure 5, it also follows that a single curve, as obtained on saw-cut cracks or derived experimentally, cannot account for the instantaneous crack morphology in different specimens (Figure 4). Although COD_{max} then turns up to be more a data acquisition method, it serves the purpose to acquire continuous and more unattended data than possible manually. Post-test corrections, as for example for compliance [7], are not

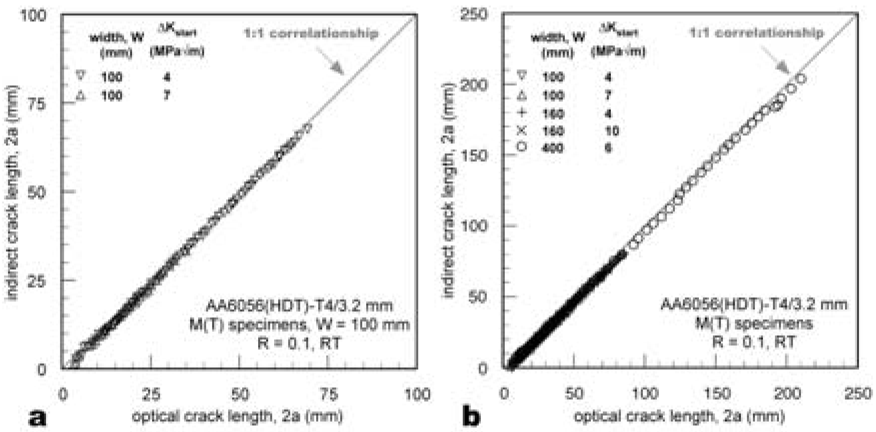

Figure 6. Correlation between direct and indirect crack length measurement, a) small width specimens (W = 100 mm), b) large width specimens (160 mm ≤ W ≤ 400 mm)

required, and the method is relatively inexpensive and simple to use. Note that the initial notch length ($0.019 \leq 2a_n/W \leq 0.020$) was by a factor of ten shorter than that recommended for compliance [5], which depicts the advantage of the COD_{max} method to obtain more data.

Examination of the Specimen Width Effect. Small width specimens are attractive for testing, since material less is required and small capacity machines can be used. However, as mentioned, questions about data validity cannot be ruled out for different reasons. Here, the data equivalency, the quality of overlapping, and the extent of scatter deserve considerations. On the other hand, despite the mixed mode crack propagation (Figure 4), there was at least a good correlation between the direct and the indirect crack length measured (Figure 6). Thus, since effects related to fracture mode or crack morphology were already incorporated in the individual calibration curve (Figure 5), the reliability of data derived, da/dN and ΔK, should be improved. The fatigue crack propagation data are shown in Figure 7.

These data are in fact obtained using different parameters (as noted in Figure 7). In the interest of achieving more data, the initial notch was kept very short. This had the disadvantage that the maximum load levels required increased with the increase in the width and the ΔK_{start} level. Therefore, different machines were to be used for testing. In turn, the precision of servo-control may not be identical from machine to machine and contribute to the difference in data. Additional parameters were the specimen width and the test frequency. Tests were also conducted using optical crack length measurements. In that case the test was halted during optical data acquisition acquired manually (test interruption effect [5]).

When tested at a higher ΔK_{start} level, the curve shifted slightly to faster propagation rates, particularly in the range of about 12-20 MPa√m. Nonetheless, the majority of data falls within a narrow range (±33 %; shown by shadowing in Figure 7) even as the ΔK_c value ($K_{max} \rightarrow K_{Ic}$) in the fast propagation regime is approached. Within the experimental allowance of ±33 %, the crack growth rate is found to be nearly identical over a wide ΔK range ($6\ MPa\sqrt{m} \leq \Delta K_{start} \leq 50\ MPa\sqrt{m}$). This would not have been possible by assuming a single calibration curve for all specimens (Figure 5).

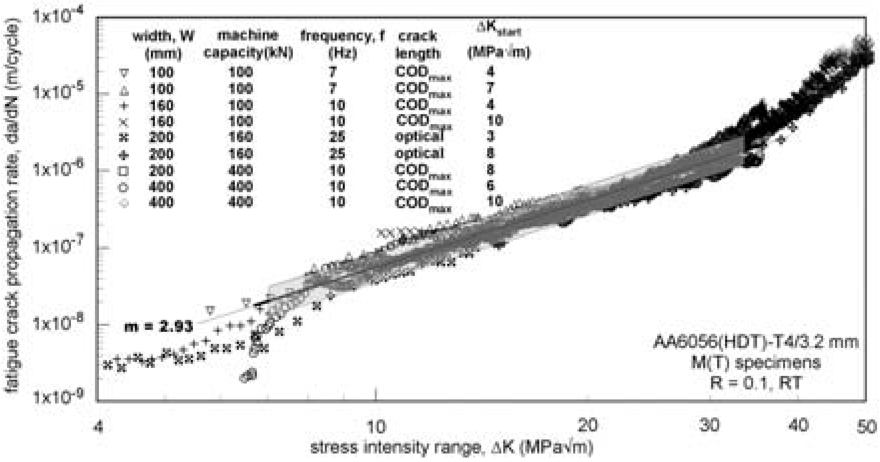

Figure 7. Equivalency of fatigue crack propagation data obtained with different parameters and the absence of the specimen width effect, the scatter range is shown by shading

Given a consideration that variability up to a factor of 3 may have to be accounted in the mid-regime fatigue crack propagation [1], the COD_{max} method is found to yield reproducible results within a very narrow scatter range. Note also that the potential drop method is difficult to use for Al-alloys due to low resolution (DCPD), weak skin effect (ACPD) or when surface contact occurs at low load ratios, since the compliance method when crack closure occurs.

To sum-up, in the present case a specimen width effect on fatigue crack propagation is found to be absent. In other words, crack propagation data can be obtained on small width specimens. This is relieving from experimentalists' viewpoints. Thereby, although very simple, the COD_{max} method has proved to be very useful and is found to be as good as the optical method (Figure 6). Since sophisticated instruments such as stable external power source, lock-in-amplifier or precision voltage drop measurement are not required and a machine internal amplifier can be used, the method is non-expensive, estimated to cost only a fraction of that required for potential difference methods. Moreover, the displacement gauge signal is sufficiently strong to achieve a good resolution even for short crack lengths. As to the crack closure measurements, principally, the COD-signal loop can be automatically recorded. Thus, in our opinion the COD_{max} method is very suitable for semi-automatic testing. It needs to be recalled that the shape of COD_{max} versus direct crack length is not unique (Figure 5). Hence, the calibration curve should to be obtained for each and every specimen. Once this is accounted for, the method yields data within very low scatter range (Figure 7). We have been using this method also for different materials such as steels, Ti-alloys, and Mg-alloys. Our experience shows that the COD_{max} method is suitable for welds also [29-31].

Conclusions

The COD_{max} signal obtained from the load-line displacement gauge is used as a parameter for indirect fatigue crack length measurement of M(T) specimens of different widths and the following conclusions are reached:

1. Since the shape of COD_{max} versus direct crack length differs from specimen to specimen, the calibration curve should to be obtained for each and every specimen. Once this is accounted for, the COD_{max} method yields fatigue crack propagation data within very low scatter range.
2. As regards full automation, the COD_{max} method is not so advantageous since optical reference data are required for every specimen for calibration, and hence the method requires manual attendance. Although it turns up then to be more a data acquisition system, it serves the purpose to acquire continuous and more unattended data than possible manually.
3. Depending on the starting ΔK value, the fracture mode varied between tension, shear, and mixed mode. Nonetheless, the fatigue crack propagation data of specimens with different

widths (100 mm ≤ W ≤ 400 mm) overlapped reasonably and scatter was low (±33 %). Thus, a specimen width effect was found to be absent for the ΔK range investigated. Hence, fatigue crack propagation data equivalent to large width specimens can be acquired on small width M(T) specimens.

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Abstract

Anwendung der maximalen Rissöffnungsverschiebungswerte für die indirekte Risslängenmessung bei der Ermüdungsrissausbreitung an mittig angerissenen Zugproben der luftfahrtspezifischen Aluminiumlegierung AA6056. Bei der Ermüdungsrissausbreitung kann wegen Bruchflächenberührung oder Rissschließung bei einem niedrigen Kräfteverhältnis sowie des Scherbruchs die Genauigkeit der indirekten Risslängenmessung durch die Potenzialmethode oder die Nachgiebigkeit (Compliance) beeinflusst werden. Als Alternative wird der Maximalwert der Rissöffnungsverschiebung, COD_{max}, genutzt. Es wurden mittig angerissene Zugproben, M(T)-Proben, verwendet, um konservative Rissausbreitungsdaten bei einem niedrigen Kraftverhältnis (R = 0,1) zu erhalten. Dünne Blechproben (B = 3,2 mm) mit unterschiedlichen Breiten (100 mm ≥ W ≥ 400 mm) aus AA6056-T4 wurden im mittleren Rissausbreitungsbereich (Paris-Bereich), der für die Schadenstoleranzanalyse von Interesse ist, untersucht. Der Gebrauch von COD_{max}–Werten lieferte indirekte Risslängen, die nährungsweise identisch mit den optisch-gemessenen Risslängen waren. Weiterhin wurde festgestellt, dass die gelieferten Daten der Proben mit kleinen Breiten denen der großen Probenweiten entsprachen. Insofern ist der Größeneffekt vernachlässigbar und die Rissfortschrittsdaten von den kleinen Probenbreiten können ebenso genutzt werden, wenn nicht genügend Material für die großen Proben zur Verfügung steht.

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