INFLUENCE OF MEASUREMENT METHOD ON FATIGUE CRACK GROWTH THRESHOLD

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Abstract

Two types of threshold tests are performed on centre-cracked tension specimens of aluminium alloy AA5083-H321. The first test is the conventional threshold test as described in ASTM E647; the second threshold test is the “constant K_{max} ,increasing K_{min}” method. A consequence of both methods is that the crack grows until the combination of applied loading and the resistance of the material are in balance. The threshold value for fatigue crack growth, ΔK_{th}, is now reached.

Three different boundary conditions of the “constant K_{max}, increasing K_{min}” test method were investigated earlier in order to determine the limits of this test method and to find if it could be used as a faster and may be better alternative for the standard ASTM method.

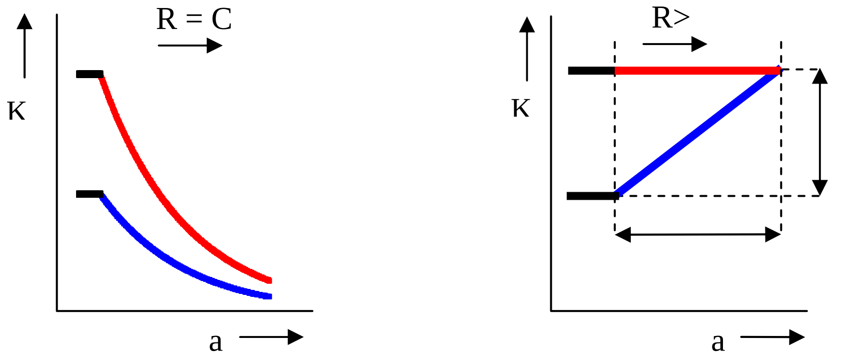
This research is extended here by studying the crack closure behaviour in the near threshold region for both types of fatigue crack growth threshold test.

Introduction

Aluminium alloy AA 5083-H321 is a moderate to high strength work hardenable alloy. The main alloying component is magnesium (4.5 weight %), mainly providing strength to the aluminium alloy by a solid solution strengthening mechanism. The alloy is widely used in marine applications because of its excellent welding characteristics and good resistance to corrosion.

In van Kranenburg et al. [1], three different boundary conditions were investigated in order to determine the limits of the so-called “constant K_{max}, increasing K_{min}” method and to find out if can be used as a faster alternative for the standard ASTM method [2]. In the first place the influence of the initial R-value was investigated. Secondly the influence of the speed of the K_{min} increase (dK_{min}/da) was studied. Finally the effect of K_{max} was looked at.

In general it was found that the agreement between these two different methods is good [3], although ΔK_{th} found by using the ASTM method seemed to be slightly higher then the ΔK_{th} that was found by using the “constant K_{max}, increasing K_{min}” method. An explanation for this behaviour is probably a different crack closure behaviour in both tests. The ΔK_{th} value that is found by using the “constant K_{max}, increasing K_{min}” method is believed to be the intrinsic ΔK_{th} value, representing the resistance of the material against fatigue crack growth. The crack closure behaviour in the near threshold region is further investigated for both types of fatigue crack growth threshold test. Crack closure is considered to be not a material property, but an extrinsic property, that is not directly a measure for the crack growth resistance. The loading scheme and characteristics of the two procedures to measure ΔK_{th} are schematically shown in Fig. 1



1a: ASTM-method *1b: constant* K_{max}*, increasing* K_{min}

FIGURE 1: Both test methods

For a lot of materials ΔK_{th} decreases as a function of increasing R. However above a critical value of R (R_c) a constant value of ΔK_{th} is found, independent of R. This result is attributed to the absence of crack closure above this critical R-value. The ΔK_{th} dependence of R in the first type of test (fig. 1a) can be found by performing tests at a range of different R-values according to ASTM E647. R is kept constant in a whole test.

Unless the closure situation is the same in both cases, it is not meaningful to compare the results obtained by ASTM E647 and by the “constant K_{max}, increasing K_{min}” method. If the critical value of R is known it is possible to compare the results of both test types if R is above the critical value R_c in both cases. In both cases now a closure free situation is believed to be present. The R-value is fixed in the ASTM method. For the “constant K_{max}, increasing K_{min}” method R increases as the crack grows. The R-value at threshold is found using the following formula:

$$R_{th} = \left(1 - \frac{\Delta K_{th}}{K_{\max,th}}\right) \qquad (1)$$

The subscripts “th” added at the three variables R, ΔK and K_{max} mean that these values are found when the threshold condition of $^{da}/dN=10^{-10}$ m/cycle is met. The threshold tests are accompanied by fracture surface research with the aid of optical and scanning electron microscopes.

Experimental details

The geometry of the specimens is a standard Centre-Cracked Tensile (CCT) specimen. The specimen have a thickness of 8 mm, a length of 340 mm and a width of 100 mm. The initial (half) notch length is 5 mm.

The chemical composition and mechanical properties are given in Table I

TABLE 1. Material properties and chemical composition (wt. %)

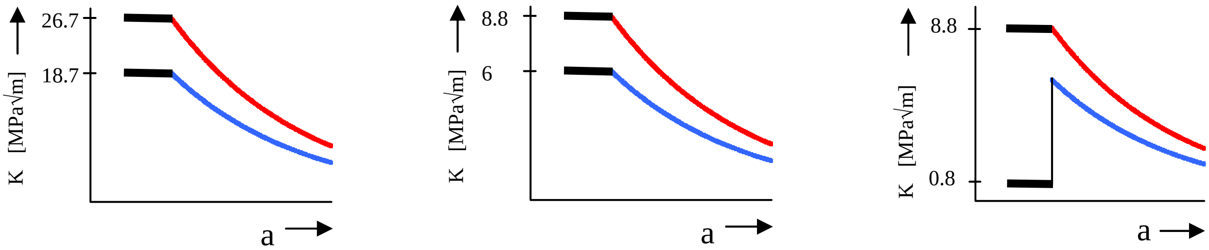
σ_{ys}, MPa	Mg	Mn	Si	Fe	Cr	Cu	Zn	Ti
240	4.5	0.65	0.26	0.22	0.09	0.09	0.06	0.03

Two tests series are conducted:

Test series 1: ΔK_{th} measurements according to the ASTM method (see fig. 1a). A range of ΔK_{th} values at different positive R-values is measured in order to find R_c and the intrinsic ΔK_{th} value. This R_c will be used to calculate a crack closure (*U*)-function in order to fit the da/dN -ΔK curves of the different R-values to one ΔK_{eff} curve. The assumption made is that U=1 for R= R_c .

Test series 2: this test series comprises both methods. Firstly a ΔK_{th} measurement procedure according to the ASTM method was applied, with deviations in the pre-cracking. Pre-cracks using different start values of ΔK and K_{max} were performed. See figure 2 and Table 2.

Secondly the “constant K_{max}, increasing K_{min}” method was applied. The constant values of K_{max} were chosen as 6, 9 and 18 MPa√m respectively, the initial R used was 0.1 and the decreasing rate of K_{min} (dK_{min} /da) was 1 MPa/√m. See Table 2.



Pre-crack: ΔK = 8 MPa √m
R = 0.7

Pre-crack: ΔK = 2.8 MPa √m
R = 0.7

Pre-crack: ΔK = 8 MPa √m
R = 0.1

FIGURE 2. Loading scheme of test series 2, all tests at R=0.7.

All tests reported here have been carried out at room temperature and normal lab air environment within a frequency range of 10-25 Hz. The tests are performed on a servo-hydraulic fatigue testing machine brand Schenk.

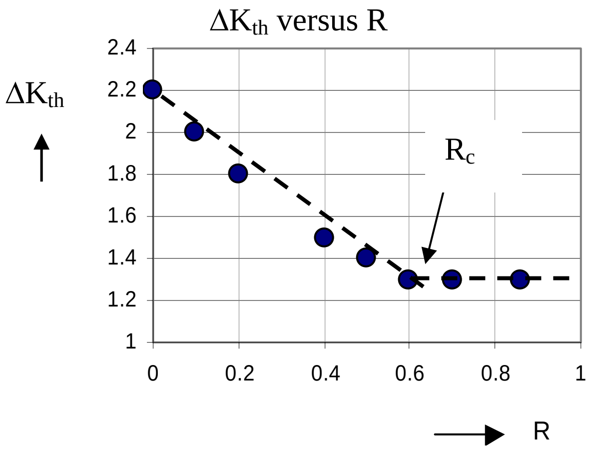
The crack length has been measured using a pulsed direct current potential drop technique. The load levels of the fatigue tests are computer-controlled during the test in order to match a pre-stored load table. The load table contains the load levels, given as function of crack length values, and is designed to control the level of K_{max} and K_{min}. For the test series in which the ASTM method is used, a C value of –0.06, was chosen, which leads to a lower K_{max} decrease rate compared with the maximum recommended C value of -0.08. The influence of the load shedding is so minimized.

When $^{da}/_{dN} \approx 10^{-10}$ m/cycle was reached, the load was kept constant on its maximum in order to prevent the fracture surfaces from damage. All specimens were broken after the tests.

Results

In fig. 3 the ΔK_{th} values are shown, that were measured in test series 1. They are plotted versus the stress ratio R. This figure also shows that R_c is near R = 0.6. The U-function, based on this test series, is:

$$U = 0.66 + 0.56R \text{ for } 0<R<0.6 \text{ and } U=1 \text{ for } R>=0.6 \tag{2}$$



R	ΔK_{th}
0	2.2
0.1	2
0.2	1.8
0.4	1.5
0.5	1.4
0.6	1.3
0.7	1.3
0.86	1.3

FIGURE 3. Results for test series 1. ΔK_{th} (MPa√m) versus R, using ASTM E647.

ΔK_{th} values measured in test series 2 are shown in Table II. In this table test results using ASTM E647 and using the "constant K_{max}, increasing K_{min}" are shown for comparison.

TABLE II. Loading data and results for test series 2, $^{dK_{min}}/_{da}$ is 1 MPa/√m.

ASTM	ΔK_{th} [MPa√m]
K_{max} = 26.7 MPa√m Pre-crack R = 0.7	1.9
K_{max} = 8.8 MPa√m Pre-crack R = 0.1	1.3
K_{max} = 8.8 MPa√m Pre-crack R = 0.7	1.3

constant K_{max}, increasing K_{min}	ΔK_{th} [MPa√m]	R_{th}
K_{max} = 6 MPa√m R_{start} = 0.5	1.1	0.8
K_{max} = 9 MPa√m R_{start} = 0.7	1.1	0.86
K_{max} = 18 MPa√m R_{start} = 0.75	1.1	0.93

As can be seen in Table II, different ΔK_{th} values were found by using the two different methods. This is contradictory with the believe that ΔK_{th} should have an unique value in case that $R > R_c$.

It is clear that a high K_{max} at the start of the ASTM test leads to a high ΔK_{th}. Such an effect is not found for the "constant K_{max}, increasing K_{min}" test. Here no dependence of the initial value of K_{max} is found.

Discussion

Fatigue crack propagation near-threshold is more complicated than that in Paris regime. The fatigue threshold behaviour is not only very sensitive to the material properties and the environment, but also to the loading system. In general the fatigue crack growth in the threshold region is associated with a sliding mode, e.g. a mode II component is present. Crack growth is largely confined to select crystallographic planes, {111} planes in aluminium alloys. Often a faceted fracture surface is observed.

Fig. 4 shows two $^{da}/_{dN}$ -ΔK curves in the near threshold area. They were found by using the ASTM method and the "constant K_{max}, increasing K_{min}" method. The ASTM curve was performed with a high R (0.7) so that $\Delta K = \Delta K_{eff}$. In the second method R is variable. In the graph four characteristic points (A-D) are shown:

A : start of a "constant K_{max}, increasing K_{min}" test. The test starts with R=0.1 and a K_{max} of 6 MPa√m.

A-B : this range shows a difference in the results found by both methods. The cause of it is that the "constant K_{max}, increasing K_{min}" method is influenced by crack closure leading to $\Delta K > \Delta K_{eff}$. For the ASTM method however $\Delta K = \Delta K_{eff}$ at the high R=0.7.

B : at this point both curves coincide. R has grown now to about 0.6 in the "constant K_{max}, increasing K_{min}" method. This means that also here a crack closure free situation has come into existence.

B-C: the results are the same for both test methods. For both $\Delta K = \Delta K_{eff}$.

C : The ASTM curve shows a sudden change in slope. It is suspected that from here crack closure starts again despite the high R-value. The reason probably lies in the very low load level near the end of crack growth. This is not observed in the other method, where K_{max} and R are relatively high and a closure free situation is (assumed to be) maintained.

D : Now also the "constant K_{max}, increasing K_{min}" method shows a transition in crack growth rate. This transition is lower than for the ASTM method. The crack growth here stops in a closure free situation, meaning that the corresponding ΔK_{th} is a real intrinsic material property, that is not influenced by an extrinsic phenomenon as crack closure.

Note that by definition ΔK_{th} is reached for $^{da}/_{dN} = 10^{-10}$ m/cycle. In figure 4 it is shown that this definition can lead to problems if we compare both methods. The ASTM method has its transition point above 10^{-10} m/cycle, while the "constant K_{max}, increasing K_{min}" method has its transition point below it. For this material a value of 10^{-11} m/cycle probably would be a better criterion, although the physical meaning of it is doubtful, because it is lower than the inter-atomic spacing. However it may be clear that in either case the ASTM method seems to lead to a higher ΔK_{th} probably due to extra crack closure, that can be due to the load shedding technique, or due to fracture surface roughness, that is becoming important at the very low crack opening near the threshold (see principle in figure 4). The fact that ΔK_{th} is constant above $R=R_c$ for this material may be an indication that we have to do with a constant (extra) closure level, pointing to a fracture surface roughness induced closure. The different influence of a more or less constant closure level on both methods is schematically shown in fig. 4 too.

The micrographs in fig. 5 give further proof of a difference in closure behaviour near the threshold. This figure shows micrographs of the fracture surfaces in the threshold region (at $^{da}/_{dN} \approx 10^{-10}$ m/cycle). The fracture surfaces of samples resulting from both methods are observed. The fracture surface of the ASTM sample in the near threshold region, (C), is smooth, while the surface of the “constant K_{max}, increasing K_{min}” method (D) is rough. The fracture surface of the ASTM sample is probably smoothed by friction between the fracture surfaces. So, a considerable proportion of the fracture work is dissipated because of friction. It means that the ASTM method will not reach a crack closure free situation. This is in agreement with the higher ΔK_{th} compared with that of the “constant K_{max}, increasing K_{min}” method.

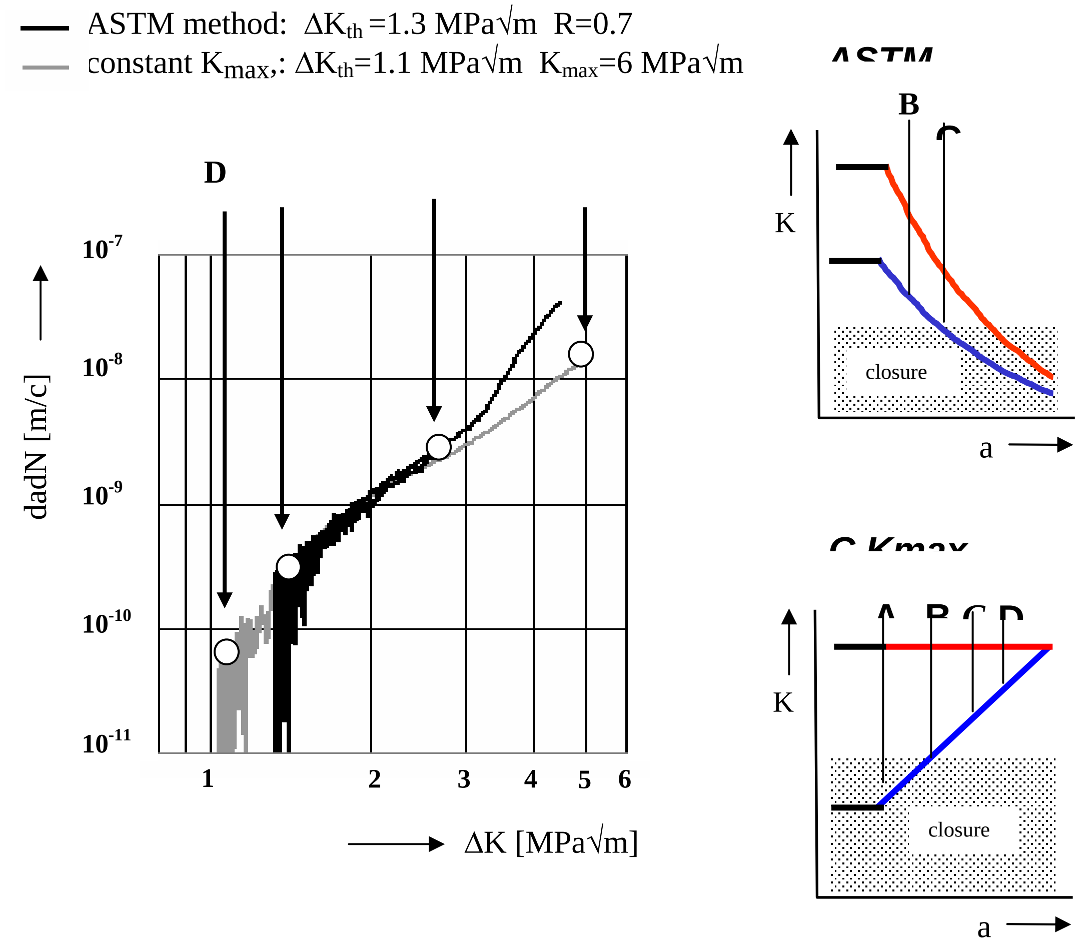


FIGURE 4: dadN versus ΔK with loading schemes

Conclusions

The conclusion that we draw is that the ASTM method leads to higher ΔK_{th} values than the “constant K_{max}, increasing K_{min}” method. The result from the latter method is believed to represent the intrinsic material resistance against fatigue crack growth, while the ΔK_{th} found using the ASTM method is higher due to crack closure that can even arise at high R-values near the end of the decreasing K test. Besides that there is also a time difference resulting from both methods. Only one-third of the cycles that is needed in the ASTM test is used in the “constant K_{max}, increasing K_{min}” test to find ΔK_{th}.

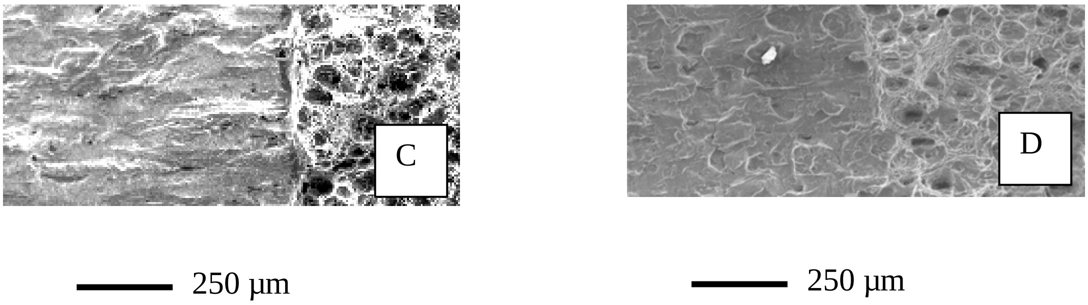


FIGURE 5: fracture surfaces in the threshold region

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