EFFECTS OF (INITIAL) FRACTURE MODE ON FRACTURE TOUGHNESS AND/OR STRESS INTENSITY.

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Many materials, subjected to fatigue loading, show shear lips on the fracture surface in the area just before failure of a test specimen (or construction). Failure is supposed to be caused by a fracture mechanics parameter exceeding a critical value. This critical value can be found in laboratory tests using standard specimens and standard techniques. In all standard tests the test is started with a two dimensional (prefatigue) crack perpendicular to the loading direction. In general no attention is paid to the initial fracture mode, i.e. there might be a difference in fracture mode between standard test and actual failure of a construction.

INTRODUCTION

The influence of the fracture mode on the fracture toughness and/or stress intensity is studied. Two kinds of tests have been performed. First the critical K_{max} found in fatigue tests (in lab air at 10 Hz) on 10.3 mm thick center cracked tension specimens of Al-2024 is discussed.
Secondly K_c (or K_{Ic}) found in tensile tests on 12.3 mm thick compact tension specimens of Al-7075 is considered. The material thickness of 12.3 mm is sufficiently large to find a valid K_{Ic} value with the standard compact tension specimen with a chevron notch. The aim was to compare specimens, with a tensile mode prefatigue crack, with specimens with single shear and double shear cracks.

EXPERIMENTS AND RESULTS

A survey of the fatigue tests on the center cracked tension specimens of 2024-T351 is given in table 1. The specimens had a length of 300 mm and a width of 100 mm. Constant amplitude tests were performed with $S_{max} = 120$ MPa at $R = 0.10$ and $R = 0.70$ respectively. Complete shear (single) was found in the tests

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at R = 0.10, while for R = 0.70 the shear lip width was much smaller at the point of instability. The crack lengths at the onset of instability were 36.0 mm, 36.0 mm and 34.0 mm for R = 0.10 (2 tests) and R = 0.70 (1 test) respectively.

TABLE 1 Results of fatigue tests on Al-2024.

Fatigue loading parameters			Results at instability failure		
type of load	R	Number of tests	a (mm)	shear fraction	K_{max} (MPa√m)
constant amplitude S_{max} = 120 MPa	0.10 0.70	2 1	36.0/36.0 34.0	complete partial	61.8 56.5
S_{max} = 120 MPa ΔK_{eff} = 5 MPa√m	variable	1	33.5	very small	55.3

Another test was performed with ΔK_{eff} = 5 MPa√m and S_{max} = 120 MPa, which implies that R must increase during the growth of the crack. This was achieved by computer control of the minimum load using a potential drop signal for the crack length measurement. The applied stresses S_{max} and S_{min} , and S_{op} (using Elber's crack closure formula (1)) are shown in figure 1. The fracture surface remained in the tensile mode almost until the beginning of instability. Slightly before instability occurred, the crack probably moved so fast that the pulsed direct current potential drop method was not fast enough to enable full control of the required cycle load. That means that just before instability ΔK_{eff} could increase. Very small shear lips were observed in this area. The resulting crack length at instability for this specimen was 33.5 mm. The results show that smaller shear lips and thus more tensile mode failure, has led to a smaller crack length at the moment of final failure, and thus to a lower K_{max} value at failure.

The result suggests that K in the shear mode is *at least* 12% lower than K for the tensile mode, i.e. if K_{max} at fracture instability is defined as K_c then the conclusion is that the crack has to grow longer before K_c is reached in a shear mode situation. In theory K and thus K_c is assumed to be only valid for tensile mode cracks, thus K_c = 55.3 MPa√m for this thickness of the material.

In order to study the effect of shear lips on the critical value of K in plane strain (K_{Ic}) , tests were carried out on compact tension specimens of the high strength 7075-T6 Al alloy. The experimental procedure was as close as possible to the ASTM E-399 standard (2), except for the initial slit and initial fatigue crack. The material thickness was 12.3 mm, which is sufficiently large to find a valid K_{Ic}

value for this material using the standard compact tension specimen with a chevron notch. The aim was to compare specimens with a tensile mode prefatigue crack, with specimens with single shear and double shear cracks. In order to obtain this, some of the specimens had to be modified. As shown in figure 3 a slotted hole was made in these specimens to allow the spark erosion apparatus to make the necessary notches of about 3 mm length. A prefatigue crack was grown in the specimens afterwards. The prefatigue zone could not be too large because the effect of the slant cracks diminished by the growing of tensile mode zones in it (figure 2). The length of the prefatigue zone was about 2 mm. A survey of the tests is given in table 2.

TABLE 2 Results of "static" K_c tests.

Specimen 7075-T6 t = 12.3 mm	type of crack	Number of tests	Nominal K_c (MPa√m)	Corrected K_c (MPa√m)	Ratio of K_c
compact tension	tensile mode type a	6	25.8		
compact tension with slotted hole	tensile mode type b	6	29.8	25.8	1
	single shear type c	4	59.2	51.0	2
	double shear type d	5	44.4	38.3	1.5

The standard specimen was used to get a calibration for the K-factor of the specimens with a slotted hole and to have the possibility to compare results with results from the literature. The critical K-factors found for test specimens of type a and b, using in both cases the K solution for a compact tension specimen of type a, are the basis for the correction factor.

The nominal K_c (i.e. calculated with the K-equation for a compact tension specimen (1) rose from 25.8 for the standard compact tension specimen to 29.8 for the slotted hole compact tension specimen , an increase by a factor of 1.16 (see table 2). This factor was then applied to the specimens with slant cracks. The corrected values in the last column of table 2 indicate a large effect of the fracture mode. A K_c value of 25.8 MPa√m is obtained for this material, which agrees very well with the valid K_{Ic} of about 25 MPa√m, usually found for this material in the literature.

For all test results it was checked whether they satisfied the ASTM E-399 standard (as far as possible for the test specimens with a slotted hole). The tests of specimens of type a (see figure 3) satisfied the conditions for a valid K_{Ic} test.

Results of two tests of the type c specimen and one of the type d specimen could not be used since an unsuitable prefatigue crack grew in the specimen. The corrected K_c results in table 2, indicate that the highest K_c is found for specimens with an initial single shear crack. The ratios of $K_{c,slant}$ and $K_{c,tensile}$ are about 1.5 and 2 respectively for the double shear and single shear cases. Thus single shear cracks show the largest effect.
The maximum shear lip width in Al-2024 is estimated to be about 5 to 6 mm [3], in 7075 it is about 1 mm. This latter effect was clearly visible on the fracture surfaces of the slant specimens of 7075. The large initial shear lip width decreases rapidly during crack growth until a width of about 1 mm. This means that for the Al-7075 specimens an initial very unstable situation with a five times too high shear lip width is created. Both initially double and single shear fracture surfaces transform to flat tensile surfaces during the unstable growth with a resulting shear lip width of about 1 mm on the edges (figure 2).

DISCUSSION AND CONCLUSIONS

If it is assumed that for the "static" tensile tests K_c is a material property (dependent on the thickness) that is independent of the initial fracture mode, the results indicate that K for a single shear slant crack is 100% lower than for a flat tensile mode crack. Both considerations, a higher K_c or a lower K, give mathematically the same result. At this moment it is not possible to choose between both descriptions that lead to a similar trend.

In a recent paper Bakker [4] shows, using finite element calculations, that the difference in K_I for a fully single shear slant crack and a flat crack is about 40% at the utmost. The difference found here is higher (100%), as found from static tensile tests on Al-7075. It might be possible that the method used to find the correction factor for the K-factor for the specimen with a slotted hole is not accurate enough, although our finite element calculations show the same result within 1% accuracy.

Anyhow, the effect is large enough to be relevant for cracks in aircraft components of the 7075-T6 alloy. Although the valid K_{Ic} for mode I cracks probably implies conservative residual strength predictions, a further study seems to be of practical interest.

The results of the fatigue tests show that smaller shear lips and thus more tensile mode failure, has led to a smaller crack length at the moment of final failure, and thus to a lower K_{max} value at instability. The results indicate that the ratio of K_{max} (at the fracture instability) for a crack, which is completely in the shear mode, and a crack in the tensile mode (with small shear lips) is 1.12. If K_{max} at fracture instability is defined as K_c then the conclusion is that the crack has to grow longer before K_c is reached in a shear mode situation. It suggests that K in the shear mode is *at least* 12% lower than K for the tensile mode.

The results of the K_{Ic} tests on 7075 Al alloy indicate a large effect of the fracture mode, much larger than found from the fatigue tests on 2024-T351 specimens. The K_c results (corrected for the initial slit) indicate that the highest K_c is found for specimens with an initial single shear crack. The ratios of $K_{c,slant}$ and $K_{c,tensile}$ are about 1.5 and 2 respectively for the double shear and single shear cases. Thus single shear cracks show the largest effect.

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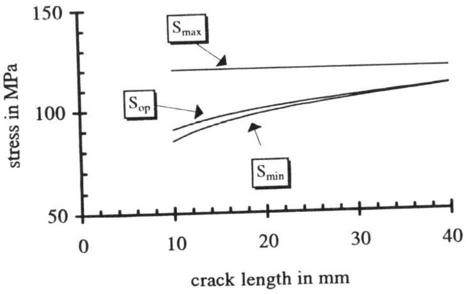


Figure 1. Values of S_{max}, S_{op} and S_{min} (S_{max} = 120 MPa and ΔK_{eff} = 5 MPa$\sqrt{m}$).

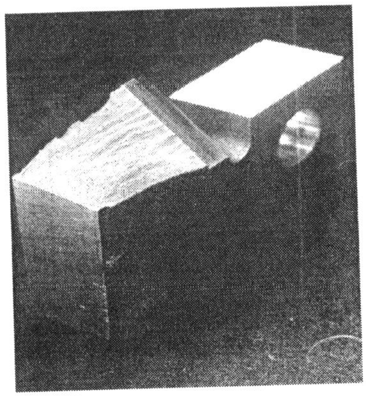
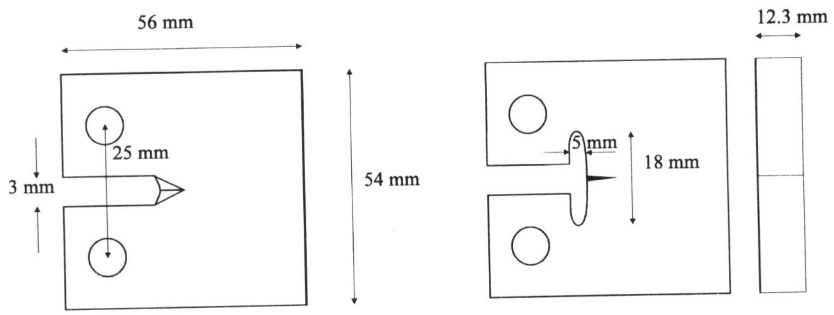
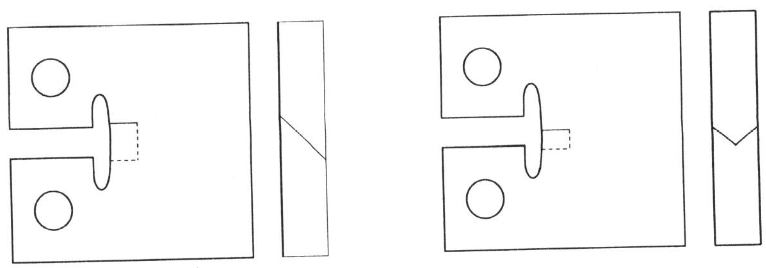


Figure 2. Photoscan of a single shear fracture surface.



a) standard specimen with chevron notch. b) initial tensile mode fatigue crack.



c) initial single shear fatigue crack. d) initial double shear fatigue crack.

Figure 3. Compact tension specimens used for K_c evaluation.