MINIMUM SPECIMEN SIZE REQUIREMENTS AND VALIDITY CRITERIA FOR K_{IIc}-TESTS

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From a discussion of the sizes of the plastic zones at the tip of a crack under shear (mode-II) and tensile (mode-I) conditions of loading hypotheses on minimum specimen size requirements for the determination of valid values of the shear fracture toughness K_{IIc} are derived. The minimum specimen thickness for a K_{IIc}-test should be smaller, but the minimum inplane specimen dimensions should be larger than for a K_{Ic}-test. Mode-I and mode-II fracture toughnesses are measured for the aluminium alloy 7075 with specimens of different sizes to verify the hypotheses.

INTRODUCTION

Fracture properties of materials in the regime of LEFM are usually determined in form of the fracture toughness K_{Ic} for tensile (mode-I) conditions of loading. Criteria for performing the test and for recording and evaluating the test data are described in the standard ASTM E399 (1) and the European proposed standard ESIS P2-92 (2). Recommendations for determining the fracture toughness K_{IIc} for inplane shear (mode-II) conditions of loading do not exist. In the literature (3-6, see also the summarizing overview 7) specimens of different types and dimensions are reported. The sizes of the specimens are often chosen on the basis of arbitary assumptions or the conditions of K_{Ic}-tests have only formally been adopted. It is the aim of this paper to develop validity criteria specifically for a K_{IIc}-test. First, requirements and criteria for valid K_{Ic}-tests and the physical reasoning they are based upon are reviewed. Following the same argumentation in an analogous manner criteria are then developed for K_{IIc}-tests. On the basis of a comparison of the plastic zones at the tip of a crack under shear (mode-II) and tensile (mode-I) conditions of loading hypotheses for minimum specimen size requirements for K_{IIc}-tests are derived. Fracture toughnesses K_{Ic} and K_{IIc} are measured with

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specimens of different sizes made of the aluminium alloy 7075 to verify the postulates. Results discussed in (8) are presented.

REQUIREMENTS FOR K_{Ic}-TESTS

The schematic graph in Fig. 1 shows fracture toughnesses measured for various specimen dimensions, where the abscissa of the diagram can be interpreted as the specimen thickness B, the specimen height H, or the ligament length (W-a). Fracture toughnesses determined under arbitary specimen dimensions B, H, (W-a) are denoted K^{I}_{c}. For specimen sizes larger than $2.5\ (K_{Ic}\ /\ \sigma_{YS})^2$, where σ_{YS} = yield stress, a constant fracture toughness value is obtained, the plane strain fracture toughness K_{Ic}. Under these conditions fracture is controlled by a plane strain state of stress prevailing at the crack tip; the load displacement record shows a more or less linear dependence up to fracture; and the fracture surfaces show a brittle cleveage crack with only small shear lips. For smaller specimen sizes ($<2.5\ (K_{Ic}\ /\ \sigma_{YS})^2$) a three dimensional state of stress prevails at the crack tip; for these conditions the values K^{I}_{c} are higher and overestimate the real fracture toughness; the load displacement record is of stronger nonlinear behaviour; and the fracture surfaces show larger shear lips.

The minimum specimen size requirements for a valid K_{Ic}-test result from conditions, that shall be discussed in context with Fig. 2. The well known "dog bone model" shows the size of the plastic zone at the crack tip across the thickness of the specimen (plotted in z-direction). A state of plane stress applies at the specimen surface and a state of plane strain in the middle of the specimen. The state of plane strain dominates, i.e. those parts of the crack front under plane stress near the specimen surface can be neglected with respect to those parts under plane strain in the middle of the specimen, if

$$B > 2{,}5\left(\frac{K_{Ic}}{\sigma_{YS}}\right) . \tag{1}$$

Furthermore, in order to achieve an overall linear-elastic response of the specimen, the size of the plastic zone must be small with respect to the inplane dimensions of the specimen (in y- and x-directions), i.e. the height H and the ligament length (W-a) of the specimen. This condition is fulfilled for

$$H > 2{,}5\left(\frac{K_{Ic}}{\sigma_{YS}}\right) \quad \text{and} \quad (W-a) > 2{,}5\left(\frac{K_{Ic}}{\sigma_{YS}}\right) . \tag{2}$$

In the following chapter an attempt is made to transfer these conditions and criteria to a K_{IIc}-test.

MINIMUM SPECIMEN SIZE REQUIREMENTS FOR THE DETERMINATION OF VALID K_{IIc} FRACTURE TOUGHNESS VALUES

A comparison is made between the sizes of the plastic zones at the tip of a crack under mode-II and under mode-I conditions of loading. As for mode-I the mode-II plastic zones are determined by the von Mises yield criterion, the calculations assume $K_I = K_{II}$ and the same yield stress in both cases. From the results shown in Fig. 3 the following conclusions can be drawn: First, the plastic zones for mode-II loading are larger than those for mode-I loading. Secondly, for mode-I loading the differences in size of the plastic zones for plane stress and for plane strain are large, but for mode-II loading they are considerably smaller.

Because of the latter argument it is speculated that the requirement of plane strain dominance of the state of stress at the crack tip can easier be established for mode-II than for mode-I, consequently

$$B^{II}_{min} < B^{I}_{min} . \tag{3}$$

With respect to the first argument it is speculated that the minimum specimen dimensions in the inplane directions y and x, i.e. the height H and the ligament length (W-a) of the specimen, must be larger for mode-II loading than for mode-I, consequently

$$H^{II}_{min} > H^{I}_{min} \quad \text{and} \quad (W-a)^{II}_{min} > (W-a)^{I}_{min} . \tag{4}$$

In order to quantify these hypotheses it shall be assumed that the fracture behaviour is controlled by the size of the plastic zone where the size shall be given by the integrated area inside the plastic zone. With this assumption one would obtain that the thickness B^{II}_{min} should be about three times smaller, the height H^{II}_{min} and the ligament length $(W-a)^{II}_{min}$, however, should be about four times larger than the equivalent values for a mode-I test.

EXPERIMENTAL INVESTIGATIONS

In order to verify the hypotheses (3) and (4) systematic measurements of the mode-I and mode-II fracture toughnesses K_{Ic} and K_{IIc} have been performed with specimens of different sizes made from the aluminium alloy 7075 (AlZnMgCu1,5).

TABLE 1- Material properties

	$R_{p0,2}$ [MPa]	R_m [MPa]	E [GPa]	A_5 [%]	K_{Ic} [$MPa\sqrt{m}$]
Al 7075	488	562	71	11	24

Some relevant material properties are summarized in Table 1.With these data minimum specimen dimensions are estimated as given in Table 2. For mode-I loading the dimensions were determined according to the ASTM requirements, for mode-II loading the values were calculated on the basis of the previous hypotheses with the additional assumption $K_{Ic} = K_{IIc}$.

TABLE 2- Minimum specimen dimensions

	Mode - I	Mode - II
B_{min}	6 mm	ca. 2 mm
H_{min} , $(W-a)_{min}$	6 mm	ca. 24 mm

Mode-I or mode-II loading was achieved in the experiments utilizing a loading fixture after Arcan (6) and Richard (7). The specimens were instrumented with clip gauges in order to measure the crack opening displacement v in mode-I tests and the crack line displacement u in mode-II tests. In all cases the fracture toughness values have been determined from the actually recorded maximum load values, i.e. an evaluation by the 5%-secant line has not been performed, in order to allow for a direct comparison of data even when slight deviations from a linear elastic response might result.

EXPERIMENTAL RESULTS

For verification of the first hypothesis, i.e. the hypothesis on the minimum specimen thickness B^{II}_{min}, fracture toughness measurements were performed with specimens of height H and ligament length (W-a) of 25 mm and specimen thicknesses B of 2, 5, 10, and 16 mm. In Figure 4, first, the results are shown of measurements of the mode-I fracture toughness K^{I}_{c}. The obtained experimental data indicate a minimum specimen thickness B^{I}_{min} of about 12 mm. For larger thicknesses a practically constant fracture toughness value K_{Ic} is obtained. An exact determination of the point of transition into a constant toughness value is difficult to achieve because of the gradual slope of the curve. This is also one of the reasons for the lower value of only 6 mm of the theoretically estimated minimum specimen thickness. In general, the measured data are in agreement with the results expected for K_{Ic}-tests. This is also true for the resulting fracture appearances. The specimens of thicknesses 2 mm and 5 mm show large shear lips, indicating a mixed state of stress along the crack front. The specimen of 16 mm thickness shows the appearance of a brittle cleavage crack with only very small shear lips.

Figure 5 shows the equivalent fracture toughness data obtained under mode-II conditions of loading. Following the nomenclature introduced for mode-I loading, fracture toughnesses determined under arbitary specimen dimensions B, H, (W-a) are denoted K_c^{II}. Specimens with thickness of 2, 5, and 10 mm were tested. Because of the limited capacity of the test machine specimens of 16 mm thickness could not be loaded up to instability. The measured data do not show any dependence of the fracture toughness from specimen thickness. Since in all cases the specimen thicknesses are smaller than the minimum specimen thickness for mode-I loading, B^I_{min}, it is concluded that the minimum specimen thickness B^{II}_{min} for K_{IIc}-tests must be smaller than the minimum specimen thickness B^I_{min} for K_{Ic}-tests. This result confirms hypothesis (3).

In the mode-II experiments the aluminium alloy used for these investigations shows a crack propagation in the direction of the ligament and not in the direction of 70° to the ligament, as is expected from a maximum tensile stress criterion. For none of the specimen thicknesses shear lips are observed, actually the fracture surfaces extend straight up to the very edge of the specimen. Such a behaviour has also been observed by other investigators (9-11) and seems to be typical for aluminium alloys. Whether or to what extend this nontypical fracture behaviour might have an influence on the results of the problem under consideration in this paper is further investigated by the authors.

For investigation of the validity of the second hypothesis (4) fracture toughness measurements are currently performed with specimens of different in-plane dimensions H and (W-a). Data of sufficient number that would allow for a direct comparison of fracture toughnesses, however, have not been established yet. Therefore, in this paper indirect conclusions are drawn from characteristics of the load displacement records that were obtained for K_{IIc}- and K_{Ic}-tests. Typical results on the dependence of the load as a function of the crack opening displacement v for a mode-I test and as a function of the crack line displacement u for a mode-II test are shown in Fig. 6. In both tests the specimen thicknesses met the requirements for mode-II and mode-I minimum thicknesses. As in the previous experiments the specimens were of the same height H and ligament length (W-a) of 25 mm.

For the mode-I test an almost linear-elastic response is observed. The measured load record is an indication of an overall linear-elastic response of the specimen and thus confirms that the chosen specimen dimensions fulfill the minimum specimen dimensions H^{I}_{min} and $(W-a)^{I}_{min}$, which is expected, since the measurements have been chosen accordingly. Contradictory to this behaviour, the mode-II test shows a stronger nonlinear response. This is an indication, that the in-plane specimen dimensions H and (W-a) are too small and obviously do not fulfill the minimum specimen dimensions H^{II}_{min} and $(W-a)^{II}_{min}$. The measured load records, therefore, give indirect indications, that for K_{IIc}-tests larger inplane specimen dimensions must be chosen than for K_{Ic}-tests. This result confirms the expected trend of hypothesis (4).

SUMMARY AND CONCLUSION

For establishing minimum specimen size requirements and validity criteria for mode-II fracture toughness tests a comparison has been made of the crack tip plastic zones for mode-II and mode-I conditions of loading. It is speculated: the minimum specimen thickness for K_{IIc}-tests is smaller, but, the minimum specimen dimensions in inplane directions, H and (W-a), are larger for K_{IIc}-tests than for K_{Ic}-tests. For verification of these hypotheses mode-I and mode-II fracture toughnesses have been determined for the aluminium alloy 7075 utilizing specimens of different dimensions. The experimental results verify the trend of the hypotheses. The reported investigations represent first steps only to establish K_{IIc} validity criteria. Also, in the theoretical estimates simplyfying assumptions have often been made, e.g. $K_I = K_{II}$ or $K_{Ic} = K_{IIc}$; furthermore, the aluminium alloy used for the experimental investigations showed a nontypical fracture behaviour. Because of these reasons it is necessary and planned to perform more investigations with additional variations of the specimen parameters and with other test materials in order to further verify the presented results.

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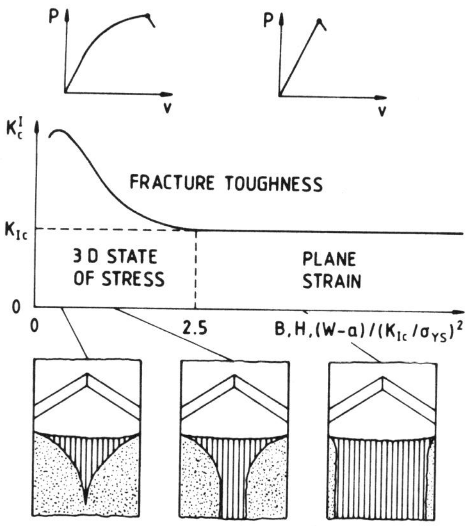

Figure 1 Dependence of the fracture toughness on specimen dimensions: thickness B, height H, ligament length (W-a)

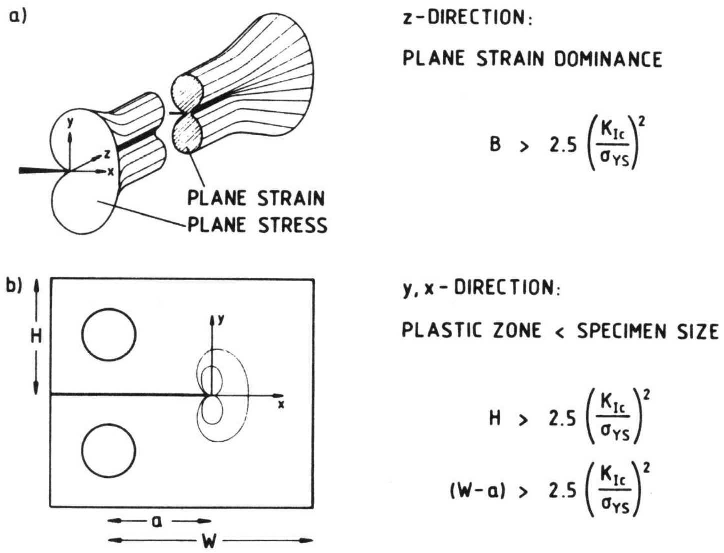

Figure 2 Crack tip plastic zones and minimum specimen size requirements for K_{Ic}-tests

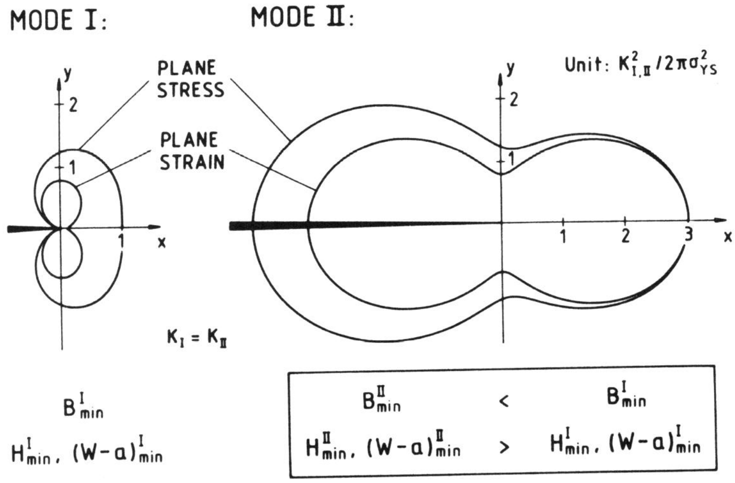

Figure 3 Crack tip plastic zones for mode-I and mode-II conditions of loading

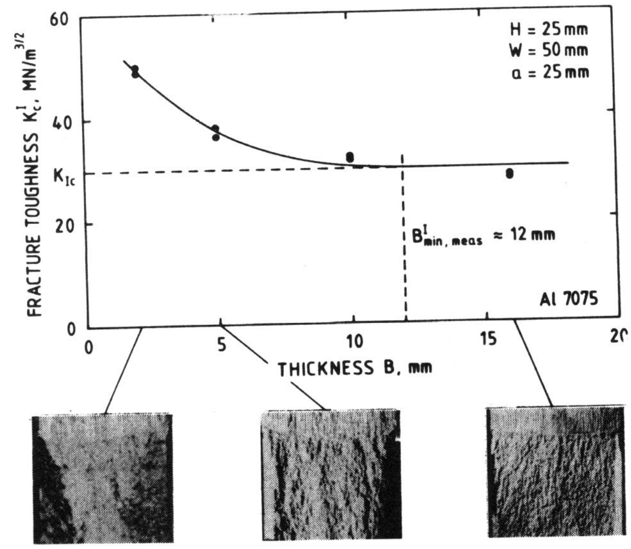

Figure 4 Mode-I fracture toughnesses measured for various specimen thicknesses

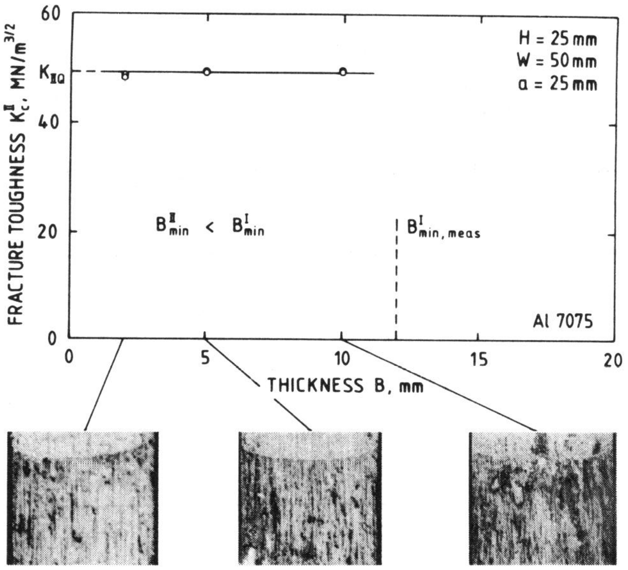

Figure 5 Mode-II fracture toughnesses measured for various specimen thicknesses

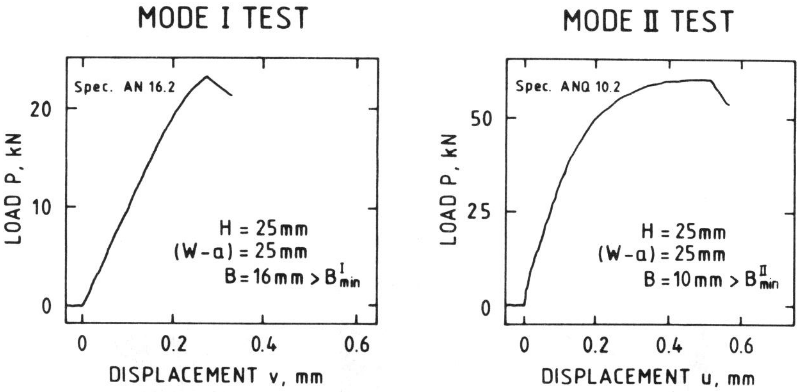

Figure 6 Load displacement records for a K_{Ic} - and a K_{IIc} -test