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A STUDY OF MODE II FRACTURE TOUGHNESS TEST STANDARDISATION OF METALS

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ABSTRACT

In LEFM, it has been predicted that under pure mode II loading a smooth test specimen would fracture at an angle of $_C = -70.5°$. However, for aluminum alloy 7075-T6, it has been found that $_C = 0$ whether the specimen is grooved or not. This apparent inconsistency has now been resolved by adopting a specimen of appropriate geometry and loading configuration, which can distinguish between plastic and brittle fracture, thereby opening the way to standardisation of the mode II fracture toughness testing of metals. Accordingly, various studies have been conducted, both by FE analysis and laboratory testing, which address the selection of suitable test specimens, the requirements of specimen configuration and the analysis of test results. As a result, it may be concluded that the proposed specimen would be suitable and a grooved specimen would be needed in order to achieve true mode II fracture.

KEYWORDS

mode II, fracture toughness, fracture testing, crack shear displacement, groove, aluminum alloy 7075-T6, compact shear specimen, test standardisation

INTRODUCTION

Interest in K_{IIC} testing has increased in recent years and various mode II specimens have been proposed [1,2]. The two commonly-used criteria to evaluate the suitability of these specimens have been i) the intensity of normal stress ahead of the crack tip which would correspond to the error in measuring K_{IIC} and ii) the compactness of the test specimen which would provide for a lower fracture load and thus minimal plastic deformation.

The intensity of normal stress ahead of the crack tip of the test specimen may be determined from the value of the ratio of K_I/K_{II} under mode II loading. If $K_I>0$ indicating a tensile normal stress ahead of the crack tip, fracture due to mixed mode I-II loading could result. On the other hand, if $K_I<0$, the compressive stress at the pre-crack face behind the crack tip could give rise to friction and overestimation of the fracture toughness. From the point of achieving a pure mode II fracture, the absolute value of the ratio would have to be as small as possible.

The compactness of the test specimen may be determined by the normalised mode II stress intensity factor

K_{II}'. A common form of the normalised mode II stress intensity factor, which is adopted in this study, is given by

$$K_{II}' = \frac{WT}{F\sqrt{\pi a}} K_{II}, \tag{1}$$

where F is the applied load, and T the thickness, a the crack length and W the width of the specimen respectively. Hence, specimens with similar dimensions of W, T and a but also smaller values of K_{II}' would need higher loading to cause fracture. However, a higher load would result in greater plastic deformation during fracture testing, which is a source of error, hence K_{II}' should be kept as large as possible.

Investigations [2,3,4] have shown that both the foregoing criteria have not been well satisfied in K_{IIC} testing. Firstly, the development of normal stresses ahead of the crack tip has seemed inevitable, and generally K_I<0 due to the effects of Poisson's ratio. As indicated in the foregoing discussion, fiction would develop as a result. Secondly, K_{II}' has been generally small compared with K_I' of mode I test specimens, where

$$K_I' = \frac{WT}{F\sqrt{\pi a}} K_I. \tag{2}$$

Thus, in taking into account the additional factor that K_{IIC} would probably be larger than K_{IC}, the fracture load in a K_{IIC} test might be expected to be much higher than that of a corresponding K_{IC} test.

Another problem in K_{II} testing has been the direction of crack extension. According to reports on brittle materials such as PMMA and tool steel [4,5], the crack would extend at an angle of about –70.5 with respect to the self-similar direction. Although this failure mode coincides with brittle fracture theory [6,7], the fracture mechanism is thought to be mode I by some researchers [7,8,9] because it is actually the near field tensile stress and not shear stress that causes the failure. On the other hand, for more ductile materials such as aluminum alloy, the crack tends to extend along the self-similar direction [10,11]. The load-displacement record in such test would become nonlinear at small loads [11], so the concepts of linear elastic fracture mechanics would not be applicable any more. Thus, a K_{IIC} value obtained under these circumstances would have some other connotation in terms of elastoplastic fracture.

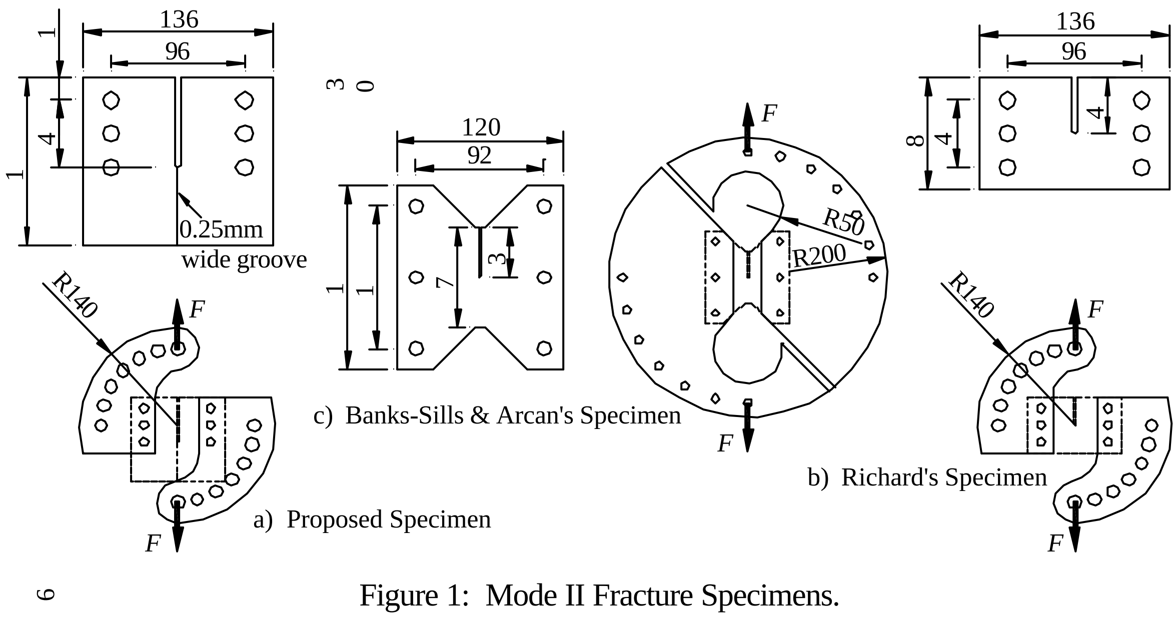

Figure 1: Mode II Fracture Specimens.

In view of the preceding considerations, a specimen for K_{IIC} testing is proposed herein which is essentially a modification of the mode II fracture test specimen originally proposed by Richard [12]. There are two aspects to this modification, as shown Figure 1(a). Firstly, the ligament length of the specimen has been extended to produce a non-uniform shear stress distribution along it under mode II loading. With this modification, a considerable reduction in the value of ½K_I/K_{II}½ as well as increase in K_{II} may be achieved. It was also found that brittle fracture could thereby be obtained under mode II loading for relatively ductile materials such as aluminum alloy, where the crack extended along the –70.5 direction. Secondly, a narrow groove was introduced in the normal direction to the face of the specimen, along the crack line and on both faces, so as to reduce the ligament thickness and assist in guiding the crack to extend along its self-similar direction and thus obtain a truly Irwin-type of brittle mode II fracture. The influence of the groove and relative stiffness of the loading fixture on the values of ½K_I/K_{II}½ and K_{II} were also investigated. In an earlier investigation [13,14], the grooved specimen was found to be appropriate for fracture toughness testing as grooving was found to have no adverse influence on the distribution of the stress intensity factor along the crack front.

K_{IIC} test was carried out on aluminum alloy 7075-T6 using the proposed specimen. It is noteworthy that in the case of K_{IIC} testing, the "pop-in" phenomenon was observed.

TEST SPECIMEN

Proposed Mode II Test Specimen

The proposed specimen and its loading fixture are shown in Figure 1(a). The specimen is an adaptation of Richard's [12] specimen shown in Figure 1(b), with the exception that the ligament of the specimen has been extended and a 0.25 mm wide has been introduced along the crack line on both faces of the specimen and normal to the direction of each face. The extension of the specimen's ligament provided a non-uniform shear stress distribution along the ligament under mode II loading, in which the shear stress was highest near the crack tip and decreased at a significant rate away from it. This ensured that plastic deformation was localised within the near field of the crack tip while zones away from it remained largely elastic. Such circumstances would be more conducive to the development of brittle fracture.

The groove, on the other hand, was introduced to hinder the occurrence of brittle fracture at –70.5 under mode II loading. As a consequent and also due to the relative weakness of the reduced thickness of ligament in the plane, a crack extension in the self-similar direction would be more imminent. The depth of grooving required would, therefore, depend on its ability to deter the non self-similar crack extension under mode II loading. In the present study, the dimensions of the specimen adopted for analysis and testing are as shown in Figure 1(a). The thickness of specimen and depth of groove were varied.

Comparison of Mode II Test Specimens

Two commonly-used mode II test specimens are the ones proposed by Richard [12] and Banks-Sills and Arcan [4], as shown in Figures 1(b) and 1(c) respectively. In the present study, the suitability of the proposed specimen has been evaluated by comparing it against the two specimens whose dimensions adopted for analyses are shown in the same figures.

Two-dimensional (2-D) finite element analyses were carried on all three specimens using ABAQUS [15]. Eight-noded quadratic quadrilateral isoparametric elements were used and the singularity at the crack tip was simulated by triangular quarter-point elements formed by collapsing one face of the 8-noded quadrilateral element and relocating the mid-side nodes to respective quarter-points from the crack tip, as proposed by Barsoum [16]. The respective stress intensity factors were deduced from the displacements of the crack faces accordingly. The grooved specimen was idealised as a 2-D finite element model by modifying the Young's modulus of the elements at the ligament pro-rata to reflect its reduced thickness. This technique has been verified and found suitable in an earlier investigation [14].

In the present study, the material adopted for the three specimens and subsequently used for fracture testing of the proposed specimen was aluminum alloy 7075-T6 having a Young's modulus of E=72 GPa and

Poisson's ratio of =0.32. The loading fixtures of the three specimens were also presumed to be of aluminum alloy 7075-T6 for the purpose of comparison. The effects of stiffness of the loading fixture on the proposed specimen was analysed separately.

The three specimens were analysed for pre-crack lengths, a_f varying from 0.5 mm to 10 mm and corresponding values of ½K_I/K_{II}½ and K_{II} are shown plotted against pre-crack length for the three specimen in Figure 2(a) and 2(b) respectively. Generally, the value of ½K_I/K_{II}½ was lower while K_{II} was higher for the proposed specimen suggesting that it is the most compact specimen and at the same time experiences the least influence from a normal stress ahead of the crack tip. Furthermore, an optimal pre-crack length of approximately 3 mm is suggested in Figure 2(a) for the configuration of the proposed specimens at which the value of ½K_I/K_{II}½ would be zero. This is not apparent in the case of the other two specimens. Also a pre-crack length of 3 mm would be appropriate from the point of view of Figure 2(b) as there would be no significant increase in the value of K_{II} with pre-crack length from then on. Hence, based on the foregoing considerations, it would appear that the proposed specimen would be the most suitable for mode II fracture testing.

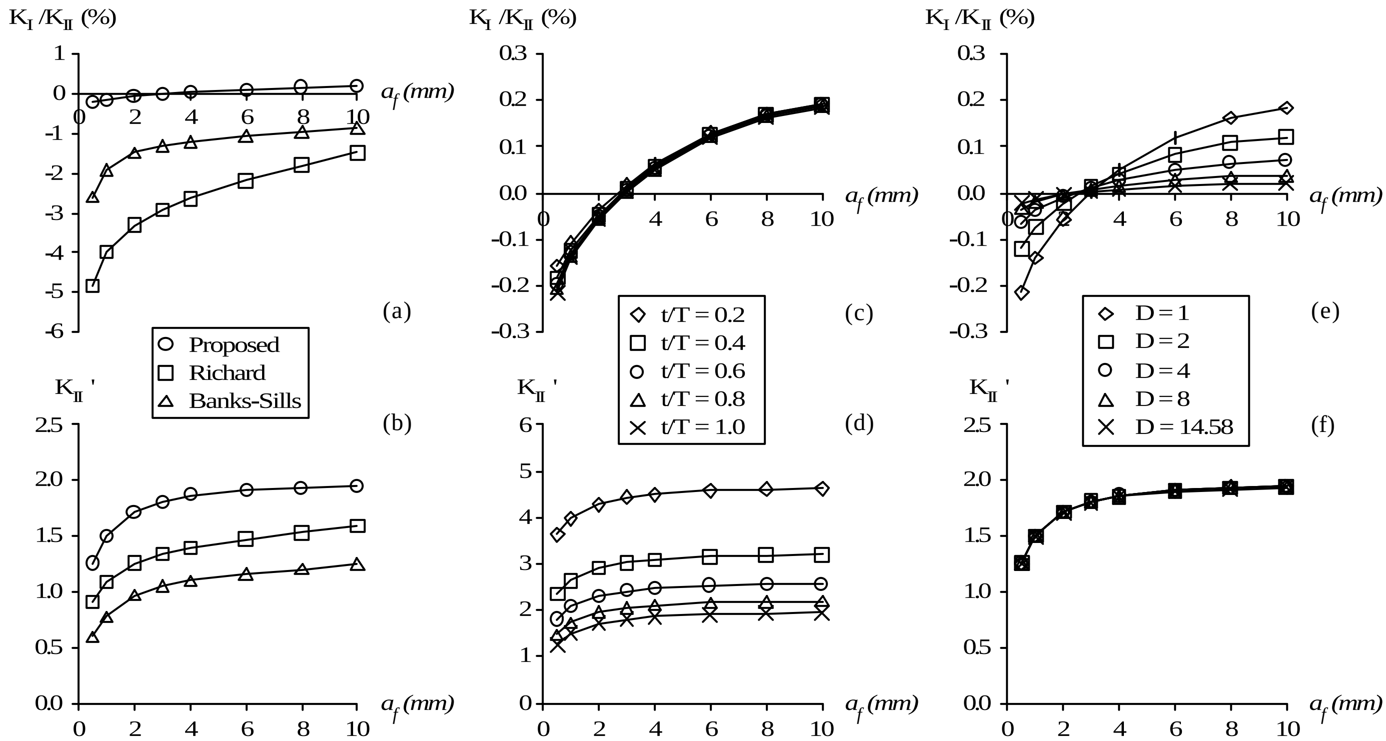

Figure 2: Analytical Results.

Investigation of Grooving and Loading Fixtures

As indicated in the foregoing discussion, the application of a groove to the faces of the proposed specimen would be a necessary feature of mode II fracture testing. Hence, the influence of grooving on the two characteristic parameters ½K_I/K_{II}½ and K_{II} has been examined. In the analyses, the groove depth was varied such that the ratio of ligament thickness after and before grooving (t/T) ranged from 0.2 to 1. The results have been plotted in Figures 2(c) and 2(d). In Figure 2(c), it is apparent that grooving did not significantly influence the value of ½K_I/K_{II}½ while on the other hand, as shown in Figure 2(d), K_{II} increased with depth of grooving, which, from the standpoint of compactness, would be advantageous. In both instances, the optimum pre-crack length of 3 mm was maintained.

The influence of the stiffness of the loading fixture was also examined, where the relative stiffness of loading fixture and the proposed specimen was specified as:

$$D = \frac{E_f\,T_f}{E\,T} \ , \tag{3}$$

in which E and E_f are the Young's modulus of the specimen and loading fixture respectively and T_f the thickness of the loading fixture. The analyses were carried out for relative stiffness D ranging from 1 to 14.58, where D=14.58 corresponds to the configuration used in subsequent fracture testing. The results have been plotted in Figures 2(e) and 2(f). In Figure 2(e), the value of ½K_I/K_{II}½ decreased with increase in relative stiffness and furthermore, if a pre-crack of 3 mm were used, the relative stiffness would, in principle, have no effect on the value of ½K_I/K_{II}½. However, since it is often not possible to control the pre-crack length, a stiffer loading fixture would be desirable. On the other hand, according to Figure 2(f), the relative stiffness would have practically no influence on K_{II}¢ at all. This would in turn suggest that K_{II}¢ may be taken to be a measure of compactness of the specimen as it would depend on specimen configuration alone.

FRACTURE TESTING

K_{IIC} tests were performed on aluminum alloy 7075-T6 based on the proposed specimen, a comprehensive account of which has been reported elsewhere [17]. The tests were carried out on both grooved and smooth specimens. The specimens were orientated in the LT direction of the metal and loaded via steel fixture in an MTS machine. The specimens were pre-cracked under mode I loading conditions according to the recommendations of ASTM E1820-96 [18] and thereafter grooved using a 0.25 mm wire cutter in an electro-discharge machine. The pre-crack length was kept close to 3 mm as suggested by the preceding analyses. During testing, the crack-mouth sliding displacement (CSD) was recorded using a clip gage attached to a knife edge which had been secured near the crack-mouth. Four set of grooved and one set of smooth specimens were tested in which the thickness of all specimens, T was 6 mm.

In the case of the smooth specimen, the crack extended in the –70.5 direction and in the load-CSD record of Figure 3(a), no "pop-in" was found. It is noteworthy that this observation has apparently not been reported on aluminum alloy before. In previous K_{IIC} testing [5,10,11], the crack invariably extended along the self-similar direction without satisfying brittle fracture theory. On the other hand, the proposed specimen herein is capable of developing brittle fracture even for a relatively ductile material such as aluminum alloy. Moreover, the result obtained would imply that it would not be feasible to obtain brittle mode II fracture on smooth specimen.

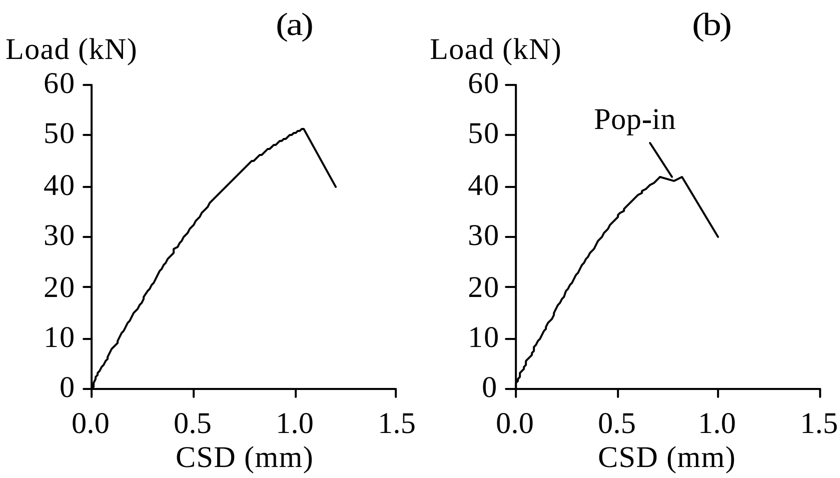

Figure 3: Experimental Results.

As for the grooved specimen for which t/T ranged from 0.68 to 0.8, the crack extended in the self-similar direction and similarly as the load-CSD record of Figure 3(b), "pop-in" was found in all tests. It is also noteworthy that this observation has apparently not been reported before in a K_{II} test. The "pop-in" load was selected as the conditional load, P_Q to calculate K_{IIC} based on the recommendations for K_{IC} testing [18]. The K_{IIC} values obtained were consistent and independent of groove depth, which appears to indicate that the grooved depths adopted were within reasonable range. The average value of K_{IIC} was $63.7\,\mathrm{MPa}\sqrt{\mathrm{m}}$ which is approximately 2.1 times the known value K_{IC} for the metal.

CONCLUSIONS

A specimen is proposed for K_{IIC} testing, for which finite element analyses and fracture tests have been performed. As a result, the following findings have been made:-

1. In comparison with the K_{IIC} specimens of Banks-Sills and Arcan, and Richard, the proposed specimen is more compact and has significantly less intensity of normal stress ahead of the crack tip. Also the influence of the normal stress may be eliminated in principle by choosing the appropriate pre-crack length of 3 mm.
2. Grooving improves the compactness of the specimen while an increase in the stiffness of the loading fixture reduces the intensity of normal stress ahead of the crack tip.
3. In the K_{IIC} testing of a smooth specimen, the crack extends in the $_C=-70.5°$ direction while for a grooved specimen, the crack can extend in the $_C=0$ direction. "Pop-in" has been found in the load-CSD records of all grooved specimens tested. These observations have apparently not been reported before.
4. For aluminum alloy 7075-T6, K_{IIC} was found to about $63.7\,\mathrm{MPa}\sqrt{\mathrm{m}}$ which is approximately 2.1 times the known value of K_{IC} for the metal.

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