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 $\theta = -70.5^\circ$. However, for aluminum alloy 7075-T6, it has been found that $\theta = 0$ 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 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
A common form of the normalised mode II stress intensity factor, which is adopted in this study, is given by

\[ K_{II} = \frac{WT}{F\sqrt{\pi a}} K'_{II}, \]

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 \( K_{II} < 0 \) due to the effects of Poisson’s ratio. As indicated in the foregoing discussion, friction would develop as a result. Secondly, \( K_{II} \) has been generally small compared with \( K_{I} \) of mode I test specimens, where

\[ K_{I} = \frac{WT}{F\sqrt{\pi a}} K_{I}. \]

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 \( -70.5^\circ \) 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 tests 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.](image-url)
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 $\frac{1}{2}K_I/K_{II}^{1/2}$ 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 $\pm 70.5$ 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 $\frac{1}{2}K_I/K_{II}^{1/2}$ 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 $\pm 70.5$ 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 $\varepsilon = 0.32$. 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, $\alpha_f$ varying from 0.5 mm to 10 mm and corresponding values of $\frac{1}{2}K_I/K_{II}^{1/2}$ 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 $\frac{1}{2}K_I/K_{II}^{1/2}$ 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 $\frac{1}{2}K_I/K_{II}^{1/2}$ 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.

\[ \frac{K_I}{K_{II}} (\%) \]
\[ \alpha_f (mm) \]

\[ \frac{K_I}{K_{II}} (\%) \]
\[ \alpha_f (mm) \]

\[ K_{II} ' \]
\[ \alpha_f (mm) \]

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 $\frac{1}{2}K_I/K_{II}^{1/2}$ 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 $\frac{1}{2}K_I/K_{II}^{1/2}$ 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:

\[ \frac{t}{T} = 0.2 \]
\[ \frac{t}{T} = 0.4 \]
\[ \frac{t}{T} = 0.6 \]
\[ \frac{t}{T} = 0.8 \]
\[ \frac{t}{T} = 1.0 \]


\[ D = \frac{E_f T_f}{E T_f} \]  

(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 \( \frac{1}{2}K_I/K_{II}^{\frac{1}{2}} \) 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 \( \frac{1}{2}K_I/K_{II}^{\frac{1}{2}} \). 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 \( K_{II}^c \) at all. This would in turn suggest that \( K_{II}^c \) 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 \( \text{–70.5} \) 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.](image)

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, \( P_0 \) 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 MPa√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 \( \phi = -70.5^\circ \) direction while for a grooved specimen, the crack can extend in the \( \phi = 0^\circ \) 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 MPa√m which is approximately 2.1 times the known value of \( K_{IC} \) for the metal.

**REFERENCES**