# FRACTURE TOUGHNESS TESTING USING SMALL CYLINDRICAL SPECIMENS WITH RING-SHAPED CRACKS

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Conventional fracture testing in the Linear Elastic regime typically requires large specimens. A new geometry, allowing valid $K_{Ic}$ measurements on small-scale cylindrical specimens with ring-shaped crack, is described. The main advantages are ease and economy in manufacture, pre-cracking and testing and small amount of sample material required in order to get valid results. Precracking and testing procedures are discussed and comparisons are presented with K-values obtained on conventional 1TCT specimens, showing remarkable agreement in terms of average toughness values.

## INTRODUCTION

Fracture toughness testing in the Linear Elastic regime typically requires, when one resorts to conventional geometries, specimens that are large and expensive to machine, mainly due to the validity requirements imposed by widely used standards like ASTM E399. The specimens must also be pre-cracked before testing, often employing delicate servo-hydraulics. In testing practice, the main problem is usually the unavailability of great amounts of sample material, which enforces the need to consider alternative specimens.

Recently, a new geometry has been proposed and validated, allowing valid toughness measurements on small-scale specimens: cylindrical specimens with ring-shaped crack, shown in fig.1. Its main advantages, with respect to conventional specimens (C(T) or SEN(B)), are

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the following:
- machining such a specimen is simpler, quicker and considerably cheaper;
- a small amount of sample material is required;
- pre-cracking is easy and much quicker;
- the circumferential crack has no end in a plane stress region, thus the triaxial stress distribution at the notch guarantees plane-strain conditions even on a small specimen;
- the actual test is in no way different from a normal tension test.

An experimental activity on this specimen was carried out at CISE under the sponsorship of ENEL-DSR (Italian Electricity Board, R&D Division). The steel tested was a CrMoV rotor steel and two proportional sizes were considered (A-type and B-type, fig.1); all tests were conducted at room temperature.

Pre-cracking and testing were performed in accordance with suggestions reported in various references, since no agreed standard on such specimens has yet been released. Even fracture toughness calculations were made according to different formulas reported in the literature; these $K_{Ic}$ values were finally compared to the results of three tests on 1TCT specimens of the same steel.

## PRE-CRACKING THE SPECIMENS

Pre-cracking a cylindrical specimen, although easier and quicker than a conventional C(T) or SEN(B), requires more attention than actual testing; its purpose is to obtain a circumferential crack of controlled depth at the root of the machined notch. This was achieved on a rotary bending machine, applying a trapezoidal-shape bending moment on the specimen (4-point bending); the combined action of this bending moment and the rotation of the specimen brought to the initiation and controlled growth of a ring-shaped circumferential crack, which was monitored by a magnetic transducer mounted above the notch. The specimen deflection, recorded as a function of time, was then associated with the depth of the fatigue crack by a simple calibration procedure.

Ideal conditions for pre-cracking were defined after a few attempts; the main parameters that must be taken into account are:
- <u>rotational speed</u>: this must be a compromise between the duration of pre-cracking and the need to avoid excessive eccentricity or irregularity in the final ligament, which can be observed if the crack grows

too rapidly;

- applied load: this is related to the value of the stress intensity coefficient at the notch root; an excessive value would cause unsatisfactory results in terms of fatigue crack shape.

The optimum values for these parameters were found to be a speed of 4000 rpm and an applied stress intensity coefficient equal to 50-60% of the expected $K_{Ic}$ value. These conditions yield total pre-cracking times of approximately 30 minutes (less than 150000 cycles) per specimen, in opposition to the several hours normally required to pre-crack a conventional specimen.

The quality of the pre-cracking procedure is mainly given by the eccentricity of the final ligament, which must be minimised in order not to influence test results; from the activity performed, it doesn't seem to depend on the pre-cracking duration or on the final crack depth, but only on the material intrinsic variability and on the accuracy in mounting the specimen on the fatigue machine.

## TEST RESULTS AND CONCLUSIONS

Fracture testing of a cylindrical specimen is thoroughly equivalent to conventional tension testing; no displacement transducer mounted on the specimen is needed, since only the final fracture load is used to compute the critical toughness value. All 15 specimens tested showed a linear relationship between load and crosshead displacement, with fracture occurring under predominantly elastic conditions.

Two different formulas were used to calculate the critical fracture toughness $K_{Ic}$:

1) Gray formula, found in reference (1)

$$K_{Ic} = \bar{\sigma} \sqrt{\pi a F_1} \qquad (1)$$

2) Sih formula, found in reference (2) and analogous to the one reported by Tada et al in reference (3)

$$K_{Ic} = \frac{P}{D^{3/2}} F\left(\frac{d}{D}\right) \qquad (2)$$

Equations (1) and (2) can be corrected for the plastic zone effect on the stress field at the crack tip by using the effective crack lenght given by the measured crack lenght plus a correction factor related to the plastic radius. The plastic correction proposed by Shen Wei et al in reference (4) has been applied to

$K_{Ic}$ values calculated according to equation (2): in conditions of small-scale yileding, the correction is not higher than 5%.

TABLE 1 - Average fracture toughness results obtained on cylindrical and 1TCT specimens.

| Spec. type | Spec. tested | $K_{Ic}$(Gray) ($MPa\sqrt{m}$) | $K_{Ic}$(Sih-uncorr.) ($MPa\sqrt{m}$) | $K_{Ic}$(Sih-corr.) ($MPa\sqrt{m}$) |
|---|---|---|---|---|
| Cyl. (A-type) | 8 | 54.1 | 53.7 | 55.4 |
| Cyl. (B-type) | 7 | 54.6 | 54.9 | 56.3 |
| 1TCT | 3 | $K_{Ic}$ = 53.3 $MPa\sqrt{m}$ (acc.to E399) | | |

The evaluation of test results lead to the following conclusions:

1. No specific influence of specimen size was found on test results: the average $K_{Ic}$ values obtained on A-type and B-type specimens were practically identical.
2. Crack depth or ligament eccentricity do not seem to have any effect on $K_{Ic}$ values or their scatter, as Ibrahim and Stark had observed in reference (5).
3. The validity criterion proposed by Ibrahim and Stark in reference (6)

$$\frac{\bar{\sigma}}{\sigma_y} \leqslant 2.5 \qquad (3)$$

was satisfied by all specimens tested.
4. On the other hand, another validity requirement suggested by Shen Wei et al in reference (4)

$$D \geqslant 1.5 \left(\frac{K_{Ic}}{\sigma_y}\right)^2 \qquad (4)$$

was found to be satisfied only by B-type specimens. However, the fact that A-type specimens have virtually given the same results might indicate that criterion (4), though more generous than the one reported by ASTM E399, is still too restrictive.
5. The average $K_{Ic}$ values obtained on A-type and B-type cylindrical specimens compare very favourably with the results obtained on three 1TCT specimens of the same steel, as shown in Table 1.

6. The minimum Compact-Tension specimen thickness required by ASTM E399 in order to get the same valid $K_{Ic}$ value as obtained on cylindrical specimens would be approximately three times the outer diameter of the smaller specimens tested (A-type).

## SYMBOLS USED

$\bar{\sigma}$ = average axial stress at fracture (MPa)

a = measured crack depth, including notch (mm)

$F_1$ = factor related to size and geometry of cracked body

$F(\frac{d}{D})$ = factor depending on specimen diameters ratio

## REFERENCES


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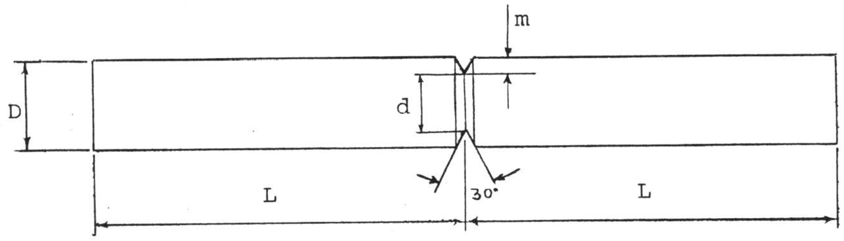


| | | | A-type | B-type |
|---|---|---|---|---|
| Outer diameter | (mm) | D | 9.4 | 12 |
| Inner diameter | (mm) | d | 6 | 7.66 |
| Notch depth | (mm) | m | 1.7 | 2.17 |
| Half-lenght | (mm) | L | 38 | 48.51 |

Figure 1 - Cylindrical specimens (A-type and B-type) used for the experimental activity.