CYLINDRICAL SPECIMENS FOR EVALUATING A SERVICE COMPONENT'S FRACTURE TOUGHNESS PROPERTIES

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Assessing the integrity and stability of a service component implies sampling as little material as possible for characterizing its mechanical properties, with particular concern for fracture toughness. This paper describes an alternative type of specimen, the cylindrical bar with ring-shaped notch, precracked by rotary fatigue and tested in tension. An extensive experimental activity has been performed at CISE under the sponsorship of ENEL-CRTN (Italian Electricity Board - R & D Division), using specimens of different dimensions and materials, both integer and weld-reconstructed. Test results are discussed in relation to different experimental variables; provided certain validity limits are met, the cylindrical specimen was found to be a cheaper and quicker mean than conventional specimens for estimating the toughness of a brittle material.

INTRODUCTION

For assessing the mechanical conditions of a service component operating at elevated temperatures, the evaluation of fracture toughness is essential, particularly when embrittlement phenomena are likely to be present due to operating temperature. Design data or specifications are seldom available, and even when they are, they give no real information on the actual component conditions: the experimentalist is left with the task of assessing its actual mechanical properties, without having to dismantle or withdraw from service the component itself. A number of test methodologies have been developed and validated in recent years at CISE Materials Laboratory, focusing on small-size specimens that allow to derive significant data from a small quantity of sample material (1,2).

Addressing the specific item of fracture toughness for a brittle (or embrittled) material, existing standards (namely ASTM E399-90) require specimens to meet dimensional requirements that are so strict that it's actually impossible to derive valid K_{Ic} data on conventional specimens such as Compact Tension C(T) or Single Edge Notched Bend

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SEN(B); moreover, machining and testing such specimens are slow and quite expensive, requiring high-capacity servo-hydraulics and sophisticated test equipment.

An alternative type of fracture specimen, the cylindrical bar with ring-shaped crack, was proposed by Shen Wei and coworkers (3) and later developed by Stark and Ibrahim (4,5). Precracking is carried out by rotary fatigue and testing corresponds to a very straightforward tensile test. Its most significant advantages, with respect to conventional specimens, can be summarized as follows:

- machining is quicker and cheaper;
- precracking and testing are much simpler and do not require high-performance test equipment;
- the notch geometry guarantees plane-strain conditions are achieved at the crack tip even on a very small specimen;
- a small quantity of material is therefore sufficient to derive significant fracture toughness data.

The aforementioned characteristics have prompted CISE and ENEL-CRTN to investigate this specimen, carrying out an extensive test campaign spanning 3 years, with the aim of validating cylindrical specimens and establishing their validity limits.

TEST PROCEDURE

Details on test procedure have been given elsewhere by the author (6). Following, main experimental aspects are briefly addressed.

Precracking. This is achieved on a rotary fatigue machine, applying a trapezoidal-shaped bending moment to the specimen, rotating at 4000 ÷ 5000 rpm. This allows a fatigue crack to propagate from the notch root in ≈ 200000 cycles; crack depth may be controlled by monitoring the specimen deflection by means of a magnetic transducer mounted over the notch. Respecting design tolerances in machining (especially for the notch area) is crucial for obtaining a sufficiently symmetrical fatigue precrack. The precracking load is such that the applied K corresponds to ≈50% of the expected K_{Ic}. Normal precracking times are 30 ÷ 60 minutes, considerably less than for a C(T) or SEN(B).

Test. A fracture toughness test on a cylindrical specimen is absolutely simple and in no way different from a straightforward tensile test; any test machine can be employed and no extensometer is needed (unless Equivalent Energy calculations are to be performed, see later on). Amongst the various formulas available in literature for calculating the critical toughness K_c, the following by Sih (7) was used:

$$K_{Ic} = \frac{P_f}{D^{3/2}} \cdot F(\frac{d}{D}) \qquad (1)$$

The inner diameter d is given by $d = D - 2 \cdot a_{eff}$, where a_{eff} (effective crack length) is the sum of the measured crack length plus a correction factor accounting for the plastic zone at the crack tip:

$$a_{eff} = a_o + 0.018\left(\frac{K_{Ic}}{\sigma_y}\right)^2 \qquad (2)$$

MATERIALS AND EXPERIMENTAL

The extensive experimental campaign conducted by CISE under the sponsorship of ENEL-CRTN focused on:

- two different steels (A - rotor steel, brittle at R.T.; B - low carbon steel, ductile at R.T.)
- various specimen outer diameters (ranging from 3 to 12 mm);
- two test temperatures (R.T. -both steels- and 100 °C -only A-);
- integer and weld-reconstructed specimens.

The complete test matrix is reported in Table 1.

TABLE 1 - Fracture toughness tests performed on cylindrical specimens and "reference" C(T) specimens.

Steel	Temp. (°C)	Specimen type	D (mm)	N. of valid tests	K_c (MPa√m)
A	R.T.	Cylindr. (integer)	3	1	42.8
			4	5	42.3
			5	6	42.0
			6	5	52.6
			9.4	10	55.1
			12	9	58.9
		Cylindr. (welded)	9.4	16	57.8
		C(T)	Thickness B = 50 mm	3	64.0
	100	Cylindr. (integer)	9.4	9	61.1
			12	10	65.7
		C(T)	Thickness B = 100 mm	1	160.1
B	R.T.	Cylindr. (integer)	9.4	12	36.2
			12	11	40.3
		C(T)	Thickness B = 25 mm	4	K_{Ic} = 224

TEST RESULTS

Tests on steel A (rotor steel - brittle at R.T.)

Results obtained on this steel were examined with respect to various test variables and to a reference K_{Ic} calculated as the mean of three valid E399-90 measurements on B = 50 mm C(T) specimens.

Fatigue crack depth. Stark and Ibrahim (4,5) found that a shallow fatigue crack alters the triaxiality of the stress field at the crack tip, thus promoting plane stress conditions and toughness overestimation. No evidence of this was found on tests results, which appear randomly distributed with respect to crack depth.

Ligament eccentricity. The same Authors (5) suggest that ligament eccentricity can lead to toughness underestimation because it introduces a bending component at fracture adding up to the prevailing tensile component. Ligament eccentricity was assumed as the percent standard deviation of the crack depth measurements made at 8 equally spaced positions along the specimen diameter; again, no detectable influence was found on the casually distributed data.

Specimen size (diameter). Fig.1 clearly shows that test results tend to decrease with decreasing specimen diameter; this is in agreement with other authors (3,5,8,9) and can be explained rather simply.

As already stated, the circular symmetry of the fatigue crack promotes an almost total plane strain condition at the crack tip of a cylindrical specimen, irrespective of its size: no part of the crack front is indeed adjacent to plane stress regions (such as lateral surfaces in conventional specimens). No artificial toughness increment is therefore present on small-size specimens, as in the case of C(T) or SEN(B).

On the other hand, in a cylindrical specimen, the plastic zone at the crack tip can extend way into the ligament and even interact with opposite plastic zones: generalized plastification of the ligament prior to fracture is bound to occur, whenever:

- the material is very ductile at test temperature;
- the specimen is extremely small.

Should this happen, stresses are beyond yield value all over the ligament, and fracture becomes a purely plastic phenomenon: calculating the critical toughness value by means of eq.(1), which is relevant to prevalent elastic conditions, causes serious underestimation of the real K_{Ic} value. The same would happen if one wanted to apply the ASTM E399-90 formula for K_{Ic} to a C(T) or SEN(B) specimen fractured after significant plastic deformation.

These remarks were confirmed by some finite element calculations performed modelling a "small" (D = 4 mm) and a "large" (D = 12 mm) specimen. Results are presented in Fig.2, where principal stresses at fracture are shown as a function of distance from specimen axis. The stress values in the "small" specimen are much higher than in the "large" one, where the ligament remains prevalently elastic and eq.(1) can successfully be used for calculating the toughness value.

Fig.3 shows test results as a function of the ligament diameter, quantified as multiple of the plastic radius $r_y = (1/6\pi)\cdot(K_{Ic}/\sigma_y)^2$. From the data obtained, it can be stated that values calculated on cylindrical specimens are sufficiently representative of the actual material fracture toughness when:

$$d \geq 10\cdot r_y \tag{3}$$

Assuming that the fatigue crack depth is such that $d/D \approx 0.5$, eq.(3) translates into the following size criterion:

$$D \geq 1.1\cdot\left(\frac{K_{Ic}}{\sigma_y}\right)^2 \tag{4}$$

analogous but more tolerant than the well-known ASTM E399-90 size criterion ($B \geq 2.5\cdot(K_{Ic}/\sigma_y)^2$) and similar to the one proposed in (3).

Test temperature. Data obtained at 100 °C are shown in Figure 4, confirming that heavy underestimation is present due to the ductile behaviour of steel A at test temperature. Application of size criterion (4) yields in this case: $D_{min} \approx 80$ *mm*.

Reconstructed specimens. The applicability of the reconstruction technique used in CISE for Charpy-V specimens was assessed by testing two series of cylindrical specimens with different length of the centre portion (15 and 20 mm), made of "precious" material, welded on two ends made of "ordinary" steel.

Results reported in Table 1 show that no influence of reconstruction was found on test data with respect to integer specimens and "reference" values, regardless of the centre portion length; slightly more data scatter was however observed on the 15 mm specimens.

Tests on steel B (low-carbon steel - ductile at R.T.)

Data obtained on steel B confirm what was observed on steel A: because of the high ductility of the material at test temperature, the ligament is totally under plastic deformation at fracture and K_c data calculated according to eq.(1) blatantly underestimate the real fracture toughness. Eq.(4) yields a minimum diameter of 539 mm!

STATE OF THE ART AND FUTURE DEVELOPMENTS

At this stage, the cylindrical specimen is restricted to the toughness characterization of brittle materials, provided size requirement (4) is fulfilled. Extending its applicability to less brittle situations could be achieved in two ways:

- applying an Equivalent-Energy-type methodology as already proposed by Wang Chang (8,9), accounting for the energy spent to fracture the specimen;
- again from an "energetic" point of view, defining an analytical formula for calculating J-Integral on a cylindrical specimen.

CONCLUSIONS

1. The cylindrical specimen is a reliable mean to characterize the toughness properties of a brittle material, allowing considerable material saving with respect to conventional geometries.
2. K_c values do not depend on crack depth or ligament eccentrity.
3. They depends heavily, however, on specimen size; a size requirement based of outer diameter was found to apply. Not satisfying this criterion leads to K_{Ic} underestimation.
4. For this reason, the cylindrical specimen is presently unsuitable for ductile materials and/or elevated temperatures.
5. Weld-reconstructed specimens are successfully comparable to integer ones and allow further material saving.

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SYMBOLS USED

P_f = fracture load (kN)
$F(d/D)$ = dimensionless geometrical factor
σ_y = material yield stress at test temperature (MPa)

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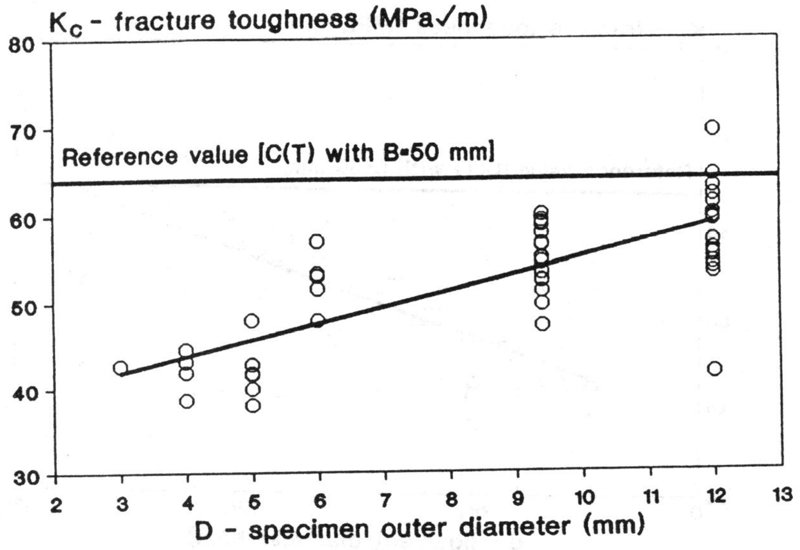

Figure 1 - Test results obtained on cylindrical specimens of steel A at R.T.

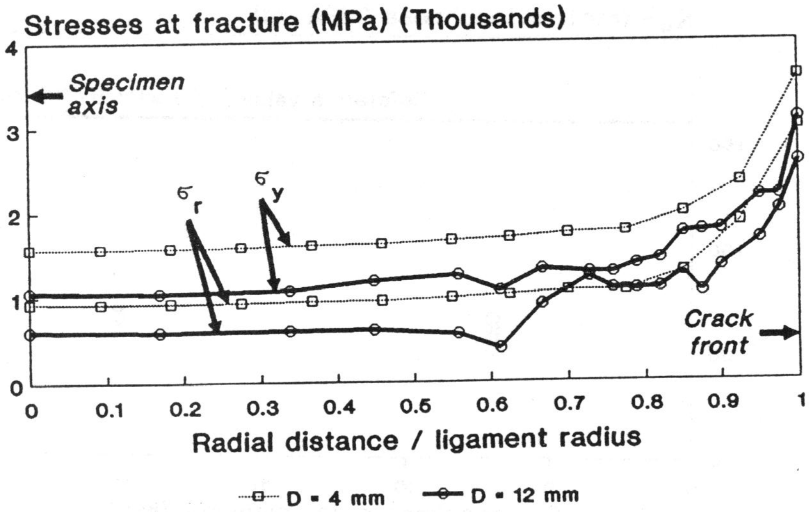

Figure 2 - Results of FEM calculations: principal stresses at fracture as a function of distance from specimen axis.

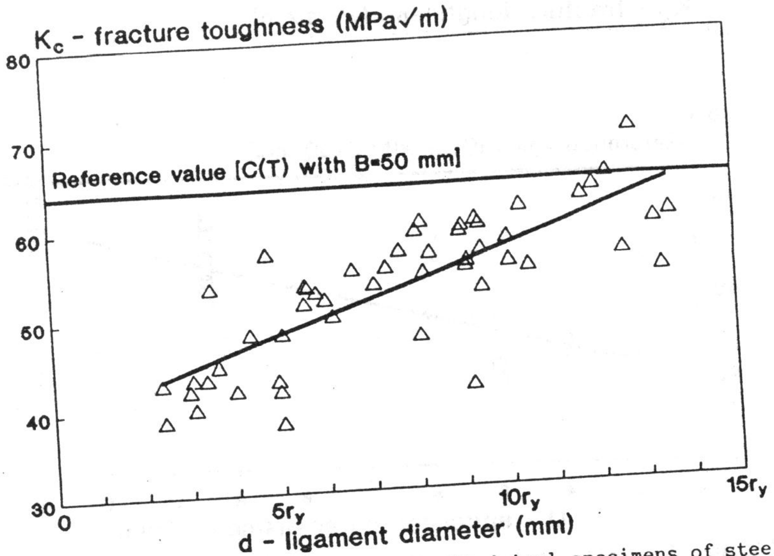

Figure 3 - Test results obtained on cylindrical specimens of steel A at R.T.

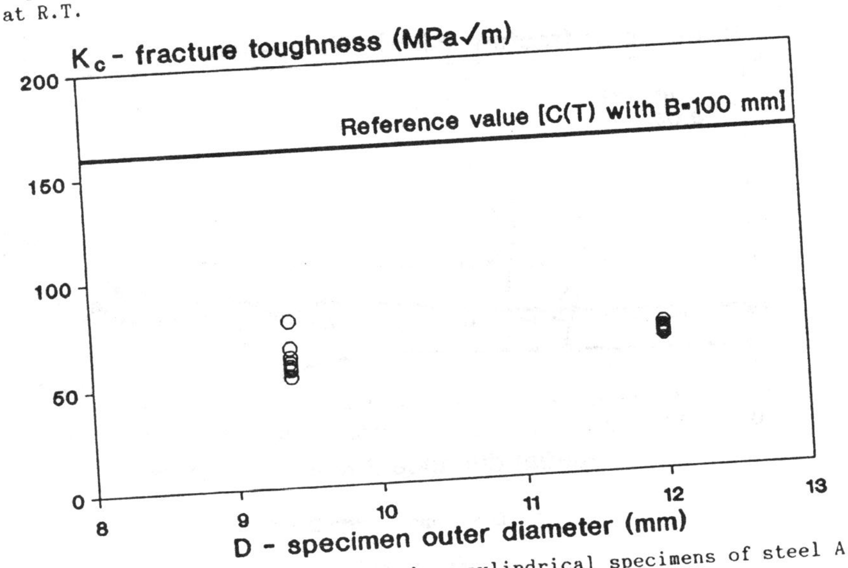

Figure 4 - Test results obtained on cylindrical specimens of steel A at 100 °C.