FRACTURE TOUGHNESS CHARACTERIZATION OF A SERVICE EXPOSED GENERATOR ROTOR WITH STANDARD AND SUB-SIZE SPECIMENS

E. Lucon*, R. Crudeli† and G. Gabetta*

An extensive experimental campaign has been carried out in order to investigate the fracture toughness of a service exposed generator rotor, withdrawn from service in 1987. Thanks to the large availability of sample material, fracture toughness tests were performed on a variety of different specimens, both standard and sub-sized. Test results are compared and discussed, and the applicability of different test geometries and sizes to residual life evaluations of service exposed components is assessed.

INTRODUCTION

For assessing the mechanical conditions of a service exposed component, the evaluation of fracture toughness is essential, particularly when embrittlement phenomena are likely to have taken place due to operating conditions. This is the case for high-pressure turbine components, where serious embrittlement may have occurred during service due to elevated operating temperatures. In the case of low-pressure or generator components operating at relatively low temperatures, like the generator rotor addressed in the present paper, the problem is that design data or specifications are normally scarce and of little usefulness, and no really reliable information is therefore available for engineering assessments: the experimentalist is normally faced with the task of assessing the component's 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 significant data to be derived from a small quantity of sample material (1,2,3).

* CISE SpA, P.O. Box 12081, 20134 Milano (Italy).
† ENEL-DPT/VDT/STE, Via A.Pisano 120, 56100 Pisa (Italy).

TABLE 1 - Chemical composition (weight %) of the rotor, measured in the bore region.

C	S	P	Al	Si	Ti	V	Cr
0.30	0.018	0.007	0.035	0.283	0.001	0.044	1.327
Mn	Cu	Ni	Mo	Sn	Sb	N_2	O_2
0.334	0.232	2.317	0.385	0.027	0.010	0.0099	0.0163

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 SEN(B); moreover, machining and testing such specimens are delicate and quite expensive, requiring high-capacity servo-hydraulics and sophisticated test equipment. The availability of a large quantity of sample material, derived from a generator rotor withdrawn from service several years ago, allowed ENEL and CISE to perform a significant comparison between toughness data obtained from conventional, standard-size C(T) specimens and several sub-size or even miniaturized specimens. This enabled some assessments to be made on the applicability and transferability of small specimen test data to the residual life evaluation of a service exposed plant component.

MATERIAL AND EXPERIMENTAL

The rotor

The generator rotor, whose sketch is shown in Figure 1, was built in Italy in 1957 under General Electric licence from an ingot cast in air after four forging cycles. A preliminary ultrasonic examination was carried out, with no indications obtained; instead, the endoscopic examination of the axial bore revealed several indications, that were removed by means of local grinding. In 1978, after 130000 hours of service, the rotor was subjected to the first in-service boresonic inspection: due to the number of defects that were found, the axial bore was widened from 78 to 110 mm and more local grinding was performed on the enlarged bore surface. The second in-service boresonic inspection was carried out in 1987, after 190000 hours of service and roughly 255 cold start-ups: the inspection revealed such a critical defectology that the rotor was finally withdrawn from service and dismantled. Hence, it became available for a vast mechanical characterization that ENEL entrusted to CISE in 1989 (4).

Material characteristics and properties

The rotor was cut into several disks, on which various mechanical, metallographic and fractographic analyses were performed; the results of the overall characterization campaign are reported in another paper presented in this Conference (4). Table 1 shows the chemical composition of the rotor, while Table 2 reports its tensile properties measured at room temperature (R.T.).

Toughness specimens and test techniques

From one of the disks, several toughness specimens with different geometries and dimensions were machined, all of them in the C-R direction and in the bore region.

C(T) specimens. Two tests on plane-sided Compact Tension specimens with B = 25 mm thickness were performed at R.T. according to the requirements of ASTM standards E399-90 and E992-86.

DC(T) specimens. Six tests (3 at R.T. and 3 at 70 °C) were performed on miniaturized Disk-Shaped Compact Tension specimens, with diameter D = 20 mm and thickness B = 7.4 mm (Figure 2). Due to the inapplicability of a conventional clip-on-gauge to such a tiny specimen, an indirect technique was applied to derive the load-line displacement values from the measured machine crosshead displacement (2). These specimens are particularly suitable to be "sliced out" of trepans machined out of plant components that must be kept in service; more details on miniature DC(T) specimens are to be found in (2,3,5).

CB(T) specimens. Cylindrical bar specimens (Figure 3), precracked by rotary fatigue and fractured by tension, were tested in two different sizes (diameter D = 6 and 12 mm). A complete description of these specimens, which allow a considerable material saving and guarantee almost total plane-strain conditions at the crack tip in the brittle regime, has been given elsewhere (6,7).

Precracked Charpy-V specimens. A complete transition curve of the dynamic toughness of the rotor was obtained from -100 to +300 °C on precracked Charpy-V specimens (PCCv), tested on an instrumented pendulum that allowed load-displacement curves to be acquired and evaluated.

TABLE 2 - Tensile properties measured on the rotor at room temperature in the tangential direction.

S_y, MPa	S_u, MPa	El_t, %	Z, %
725	914	12	42

SP specimens. Small Punch (SP) specimens are receiving increasing attention in the technical community for deriving estimates of a material's toughness properties by using an almost microscopic quantity of sample material. Tiny disks having 8 mm diameter and 0.5 mm thickness were used in this case, and literature correlations were used to derive estimates of critical toughness values at R.T.

RESULTS AND DISCUSSION

C(T) specimens. The two tests gave critical values at fracture that could not be qualified as valid K_{Ic} values according to ASTM E399-90, due to insufficient thickness; K_{EE} values were therefore calculated according to E992-86. One of the two specimens exhibited a pop-in event during loading, but the load drop and the displacement increase were judged not to be significant, and the event was ignored.

DC(T) specimens. Tests were performed both at R.T. and at service temperature (70 °C): in all circumstances, significant plastic deformation preceded the final fracture event, demonstrating that the thickness of the specimens was insufficient to guarantee a reasonable degree of stress triaxiality (plane strain conditions) ahead of the crack tip at fracture initiation. Critical values of the stress-intensity factor (K_{Jc}) were calculated from J-integral values at fracture (J_c).

CB(T) specimens. The cylindrical bar specimens are particularly suitable to estimate the plane-strain toughness properties of a brittle material, since the particular configuration of the circumferential crack guarantees nearly absolute plane-strain conditions at the crack tip. Nevertheless, if the specimen size is too small, considerable plastic deformation may be produced in the uncracked ligament, causing over-conservative toughness values to be calculated at fracture. This was the reason why two different sizes (6 and 12 mm diameter) were investigated in this case. The critical toughness values were calculated from the load at fracture using formulas found in the literature (8,9).

PCCv specimens. Strongly scattered dynamic toughness values were obtained from instrumented impact tests on pre-cracked Charpy-V specimens: this reflects the serious inhomogeneity of the material, emerging also from the general investigations (4). K_d values were obtained from maximum load values in the elastic regime and from the J-integral values at maximum load in the transition region and in the ductile regime. All load and energy values were determined from the load-displacement diagrams measured during impact. The toughness vs temperature transition curve was obtained by fitting K_d data with an hyperbolic tangent; the relevant transition temperature was found to be about 75 °C.

SP specimens. The load-deflection curve up to fracture was measured during the tests. Estimated toughness values were obtained by converting the deflection value at fracture into J_{Ic} values, by means of empirical correlations widely used in literature for pressure vessel steels (10,11). Ten tests at R.T. were evaluated.

Comparison between measured toughness values. The overall results of the experimental campaign are reported both in Table 3 (mean values) and Figure 4. Figure 5 shows a detail of the temperature range between 0 and 80 °C.

With respect to data obtained from conventional, standard-size C(T) specimens, that are to be regarded as "reference" toughness values, the following remarks can be expressed.

As expected, DC(T) specimens tested in the brittle or early transition region tend to over-estimate significantly the real toughness properties of a component; their applicability is more promising in the elastic-plastic regime, where for high-toughness materials they can meet the requirements of the Standards for deriving the critical value J_{Ic} at the initiation of ductile tearing (5).

Cylindrical bar specimens tend to give low, plane-strain estimates of the critical fracture toughness that can be safely used for assessment purposes; nevertheless, as demonstrated by test results from 6 mm specimens, small-size specimens tend to give over-conservative results and should therefore be treated with caution. A preliminary choice of the test diameter should be based on the expected K_{Ic} value of the material (6,7).

SP specimens are inadequate for estimating a service exposed plant component's fracture properties, based on literature correlations that have been developed on high toughness materials like pressure vessel steels. ENEL and CISE are presently carrying out an experimental campaign aimed at developing new

TABLE 3 - Mean toughness data obtained from the different specimens tested.

Specimen type and dimensions	Number of tests performed at R.T.	Mean fracture toughness, MPa$\sqrt{m}$
Compact Tension (B=25 mm)	2	75.7
Disk-Shaped (D=20 mm)	3	120.8
Cylindrical bar (D=12 mm)	10	67.5
Cylindrical bar (D=6 mm)	8	56.3
Small Punch (D=8 mm, t=0.5 mm)	10	116.1
Pre-cracked Charpy-V (10 x 10 x 55 mm)	1	98.0

empirical correlations for estimating the mechanical properties of service exposed turbine components from SP test data.

Finally, the K_{Id} data obtained from pre-cracked Charpy-V specimens in the lower-shelf regime normally tend to be conservative with respect to static toughness data, though in the present case the transition curve seems strongly affected by the intrinsic scatter of the investigated material (Figure 4).

CONCLUSIONS

The results of an experimental campaign have been presented, aimed at comparing fracture toughness data obtained from different specimens, both conventional and sub-sized, machined from a service exposed generator rotor withdrawn from service. Somewhat confirming previous findings, it was observed that with respect to C(T) specimens, mini DC(T) specimens tend to give unconservative high K values while CB(T) specimens may underestimate the real toughness; this underestimation is greater the smaller the diameter is. Reliable correlations still have to be developed for SP specimens to obtain reliable data on low-toughness material. Dynamic toughness tests on PCCv specimens can give an indication of the variation of fracture properties with test temperature; in the lower shelf regime, they usually tend to give low values with respect to static toughness data. In case of unavailability of large quantities of sample material, the evaluation of the fracture toughness of a brittle material can therefore be satisfactorily performed on cylindrical specimens, waiting for valuable correlations for SP specimens to be developed.

On the basis of the outcome of this test program, tests on 12 mm CB(T) specimens have been selected as the standard ENEL approach to the evaluation of the toughness properties of a service exposed plant component, particularly when just one or two trepans can be extracted from the component; if the amount of sample material is insufficient, reconstruction of the specimens by fusion welding might be taken into consideration as a perfectly reliable solution (7,8).

SYMBOLS USED

B = thickness of C(T) and DC(T) specimens (mm)

D = diameter of DC(T), CB(T) and SP specimens (mm)

t = thickness of SP specimens (mm)

K_{Ic} = plane-strain critical stress intensity factor measured at fracture according to ASTM E399-90 (MPa$\sqrt{m}$)

K_{EE} = critical stress intensity factor measured at fracture according to ASTM E992-86 (MPa$\sqrt{m}$)

J_c = critical J-integral value measured at the onset of unstable fracture (kJ/m^2)

K_{Jc} = critical stress intensity factor calculated from J_c ($MPa\sqrt{m}$)

K_d = critical dynamic stress intensity factor, measured in the lower-shelf regime from the fracture load ($MPa\sqrt{m}$)

J_{Ic} = plane-strain critical J-integral value measured at the initiation of ductile tearing according to ASTM E813-89 (kJ/m^2)

S_y = yield strength (MPa)

S_u = ultimate tensile strength (MPa)

El_t = total elongation at fracture for a tensile specimen (%)

Z = reduction of area at fracture for a tensile specimen (%)

REFERENCES

(1) Bicego, V. et al., "Fracture Behaviour and Design of Materials and Structures", Proceedings of the Eighth European Conference on Fracture, EMAS, London, 1990, pp. 1613-1620.

(2) Lucon, E. et al., "Small Specimen Test Techniques Applied to Nuclear Reactor Vessel Thermal Annealing and Plant Life Extension", ASTM STP 1204, ASTM, Philadelphia, 1993, pp. 311-323.

(3) Bicego, V. et al., "Material Damage Evaluation and Integrity Assessment of Components for Long Term Operation", presented at the First International Symposium on Microstructures and Mechanical Properties of Aging Materials", Materials Week '92, Chicago (USA), Nov 2-5, 1992.

(4) Bicego, V. et al., "Fracture Mechanics and Metallographic Analysis of the Defects in a Generator Rotor After 190000 Hours of Service", presented at the Tenth European Conference on Fracture, Berlin, Federal Republic of Germany, 20-23 September 1994.

(5) Bicego, V. et al., "Defect Assessment in Components - Fundamentals and Application", ESIS/EGF9, Mechanical Engineering Publications, London, 1991, pp. 765-780.

(6) Lucon, E., Proceedings of ECF8, EMAS, London, 1990, pp. 1077-1082.

(7) Lucon, E., "Reliability and Structural Integrity of Advanced Materials", Proceedings of the Ninth European Conference on Fracture, EMAS, London, 1992, pp. 627-633.

(8) Sih, G.C., "Methods of Analysis and Solutions of Crack Problems", Noordhoff Leyden, The Netherlands, 1973, pp.174-175.

(9) Wei, S. et al., Eng. Frac. Mech., Vol.16, No.1, 1982, pp. 69-82.

(10) Mao, X. et al., Scripta Met. et Mat., Vol.25, 1991, pp. 2481-2485.

(11) Suzuki, M., J. of Nucl. Mat., 179-181, 1991, pp. 441-444.

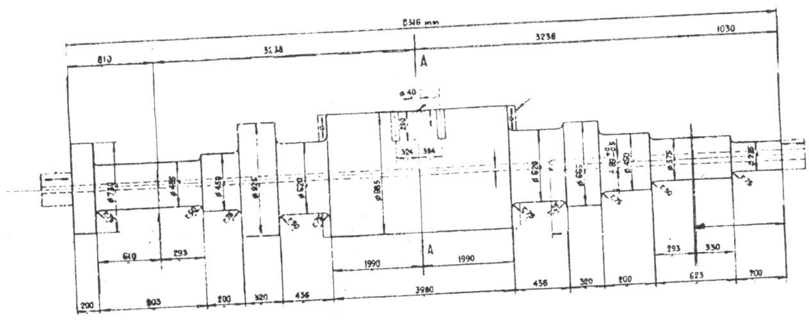


Figure 1 Sketch of the generator rotor.

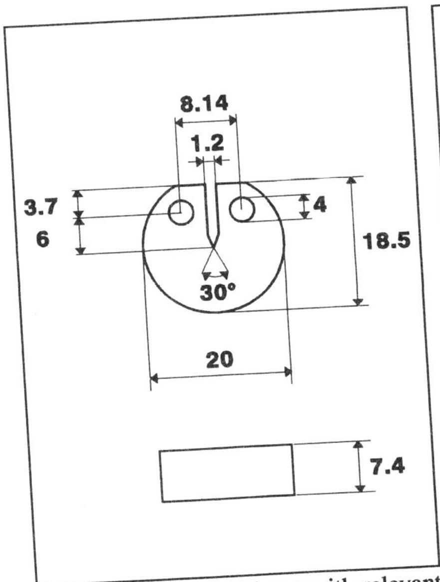
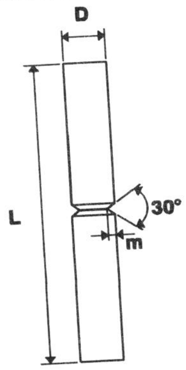


Figure 2 DC(T) specimen with relevant dimensions (mm).



D	L	m
6	48.5	1.1
12	97	2.2

Figure 3 CB(T) specimen with relevant dimensions (mm).

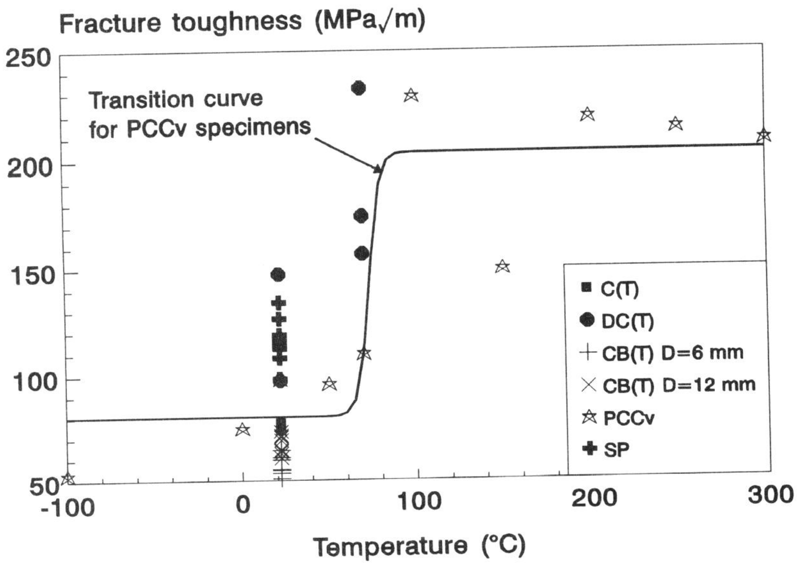


Figure 4 Results of the fracture toughness tests.

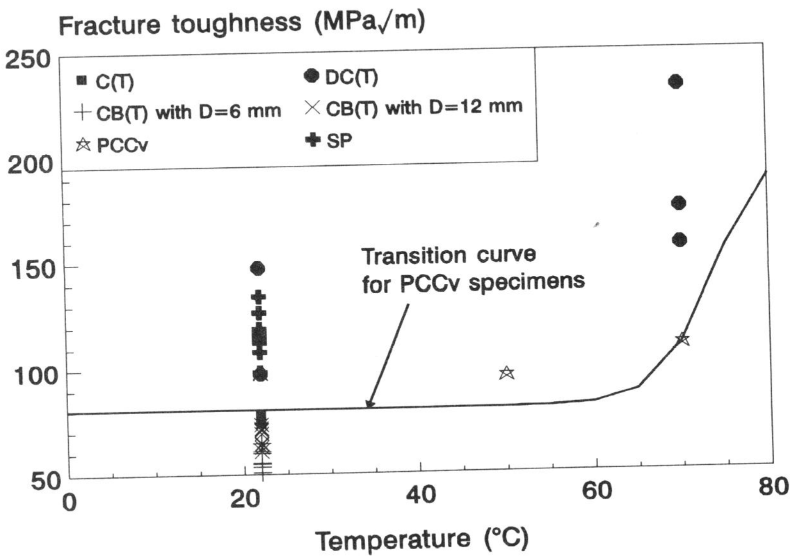


Figure 5 Detail of the temperature range between 0 and 80 °C.