FRACTURE TOUGHNESS AND FATIGUE TESTS ON MINIATURE SPECIMENS FOR PLANT COMPONENTS INTEGRITY ASSESSMENT

V.Bicego*, R.Crudeli**, C.Fossati*, E.Lucon*, S.Ragazzoni***

Following extensive adoption of damage tolerant philosophies, a trend is evident in recent years towards increasing importance of Fracture Toughness (FT), Fatigue and Creep Crack Growth (FCG and CCG) materials characteristics. A considerable amount of experimental work has been done, in recent times, at CISE laboratories utilizing miniature specimens for FT and FCG tests in the frame of ENEL (Italian Electricity Board) activities aimed at assessing integrity of critical components of fossil fuelled power stations: mainly steam turbine rotors, pipings and casings. Experimental techniques are described, procedures discussed and a short indication of ENEL assessment philosophy is given.

INTRODUCTION

The knowledge of the mechanical characteristics of the structural materials of critical plant components is a key point for reliable integrity assessments and accurate residual life predictions. Following the extensive adoption of damage tolerant philosophies, a trend is evident in recent years towards an increasing importance of materials crack growth resistance characteristics, i.e. Fracture Toughness (FT), Fatigue and Creep Crack Growth (FCG and CCG) data. Typically these data are not available for the materials of the oldest plants, which more likely require residual life evaluations and structural integrity assessments. Therefore specific tests on materials sampled directly from the components must be envisaged. In addition, even if the appropriate data were known in origin, these may be poorly representative of materials damaged after extensive operation at elevated temperatures, steady and/or cyclic loading conditions, aggressive environments. Here again experience indicates that direct information obtained from components gives a more confident knowledge of the metallurgical

* CISE, Material and Technology Division, Milan, Italy
** ENEL, Production and Generation Department, Pisa, Italy
*** ENEL, Thermal and Nuclear Research Center, Milan, Italy

condition and the residual mechanical properties of the material. Generally only small samples can be safely cut-off from a component which is to be returned into service: limitations are imposed on material sampling by geometric constraints, machining feasibility, necessity of weld repairs and concern for unforeseen high local stresses. Testing miniature specimens can be, in most cases, the only practicable approach. Creep tests on small-size specimens have been performed for a few years now in research laboratories and miniature specimens for fatigue and fracture mechanics tests are becoming more and more used.

In the frame of ENEL (Italian Electricity Board) activities, aimed at assessing the integrity of critical components of fossil-fired power stations, a considerable amount of experimental work has been recently done at CISE laboratories in setting-up procedures for miniature specimens testing. The continuous increase of electric demand and the problems encountered in the realization of new plants are in fact driving ENEL towards the adoption of a life extension strategy for its thermal units, whose average operating life is around 110.000 h, with a maximum of 220.000 h. Specific residual life evaluation procedures have been set-up for components critical for safety of operation and plant availability. When necessary and feasible, tests on miniature specimens are performed to assess the post-service components condition.

In the present paper laboratory experience gained in the use of miniature specimens in fracture mechanics and fatigue tests is discussed with particular consideration of the theoretical implications brought out by the adoption of non-conventional testing procedures.

TECHNIQUES AND PROCEDURES

For fracture mechanics tests (FT, FCG and, possibly, CCG) the Disk Shaped (DS) Compact Tension (C(T)) geometry of ASTM E399 was chosen, as it minimizes material consumption for a certain sample volume, still maintaining C(T)-type geometry and stress pattern. The dimensions (diameter of 16mm, thickness B=6mm and width W=12mm) were fixed with the aim of allowing many specimens to be machined from radial or axial trepans, cut-off from a component (the typical diameter for these carrots being 20mm), while assuring sufficient K or J capacity. A further geometry, the circumferentially notched cylindrical specimen, has been more recently considered for LEFM tests. The use of miniature specimens required the adoption of specifically tailored laboratory methods, mainly for crack length and load-line displacement measurements: the electrical Potential Drop (PD) technique for crack length monitoring and the Indirect Method (IM) for load-line displacement measurement are here considered.

An advanced version of the widely known PD technique has been implemented (1), namely the Reversing Direct Current Electrical Potential Drop (RDCEPD), similar in the concept to that originally developed by L. Coffin and co-workers (2). The d.c. current flowing trough the specimen is periodically reversed: this allows to compensate for thermal e.m.f.'s, while the use of a reference potential, measured in a region undisturbed by crack growth (mostly on a dummy specimen) at the same temperature and with the same constant current, compensates for changes in material resistivity and current fluctuations. This method guarantees the high stability and sensitivity required by the very small crack lengths of the miniature specimens. The RDCEPD technique is being extensively used in fracture mechanics (in the elastic-plastic regime) as well as in fatigue crack growth tests. During the initial fatigue precracking the method allows close control of the crack length, necessary to have as maximum ligament as feasible for subsequent testing.

The Indirect Method (3) allows the evaluation of the load-line displacement from the stroke signal of the testing machine corrected to account for machine plus load train compliance and specimen identation caused by the pins. Good results are obtained when the displacement has a large plastic component, i.e. in toughness tests in the elastic-plastic regime.

DISCUSSION ABOUT TESTS AND DATA SIGNIFICANCE

Apart from the need of particular test equipments and procedures as described above, in FT and FCG tests on miniature specimens, a number of additional problems exists. They regard not only the setting up of a suitable procedure of sampling and handling the test data, in order to provide the best quality of the results, but also the validity limits of the parameters determined from tests. The special nature of these aspects, expecially in tests performed for residual life evaluation, relies upon the fact that most procedures recommended by test standards, (ASTM will be mainly considered hereafter), were developed for conventional specimens. So in the case of sub-sized specimens one is frequently faced with non-conventional situations often bringing the need of adopting non-standard procedures to get appropriate data or to improve the quality of data; problems arise when these solutions are unacceptable in principle, as they violate basic aspects of the test philosophy itself, or when they are non-rigorous but still reasonable escamotages, or when they only vary minor aspects of the standard methodology.

Provided all of the relevant test parameters have been measured with the appropriate accuracy, the main question concerns the conditions to be met in order that the Fracture Mechanics (FM) quantities, K and J, can effectively be considered representative of the crack-tip stress field. With reference to the miniature DS specimens, the different situations which are expected to guarantee LEFM conditions in toughness (K_{Ic}) and FCG (da/dN vs ΔK) tests, or to guarantee the existence of the HRR field in J-R curve tests have to be distinctly analyzed.

K_{Ic} tests. When using the small DS specimens, most of the ferritic steels cannot provide valid K_{Ic} data since ASTM E399 LEFM plane strain condition is almost invariably violated. Only for high strength alloys such as CrMoV and NiCr forging rotor steels in the lower shelf of the transition curve the violation of such LEFM condition is moderate; in this situation more empirical schemes, such as the Equivalent Energy (EE) method (ASTM E992) can be used. Tests on serviced material are likely to be favoured in this respect, as temper embrittlement phenomena decrease the toughness and miniature DS specimens are likely to fall within a K-described stress field. In any case, even if the K_{EE} approach is used, the area under the load-displacement, P-V, curve has to be evaluated, which rises the problem of the accuracy of the displacement data. Being the typical behaviour nearly elastic, the described IM technique is inaccurate; the authors, to avoid space problems, used a special "OMEGA" type clip-gage in tests up to 100 °C on a 1CrMoV steel, spanning the deflection on the front face of the DS specimen. If some plasticity is present different K_{EE} values could be obtained from measuring V at different positions; precise evaluation of this effect is difficult, and ASTM E992 does not exclude out-of-load-line positions of the clip-gage, suggesting that if the behaviour is nearly elastic the error should be small but, quite in contradiction, a minimum of absolute accuracy for the clip gage is recommended. These ideas suggest that the current way to treat test data slightly beyond the LEFM limit is not perfectly clear. Sometimes K_J values obtained from J are considered (in place of K_{EE}) but this procedure strictly relies on V_{LL} data availability. Elastic and plastic rotational factors can be used to estimate V_{LL} from V data; in lack of the appropriate expressions for the DS geometry, the authors tried an elastic C(T)-derived rotational correction to the V data provided by the OMEGA gage: K_J values were systematically 20% lower than K_{EE} data. It could not be clarified if the discrepancy was due to errors in K_J (use of C(T) rotational correction, plastic rotation not considered ....) or in K_{EE} evaluation or whatever else. At present it may be concluded that, for tests in the early transition region, as plasticity is growing the reliability of toughness data, no matter the way they are obtained, is progressively lost and existing knowledge should be improved by the scientific community.

J-R curves. In these tests the IM technique previously described for V_{LL} measurements is applicable to the miniature DS specimens. Main problems involve the so-called J-capacity (dimensions sufficient to allow an HRR field to exist at the crack tip) and the maximum extent of crack growth which can be considered to provide valid J-Δa data. The situation is depicted in fig. 1. All these limitations are function of material characteristics (at test temperature) and specimen geometry, and are not available for the DS geometry: for this reason the criteria for the C(T) specimens are generally assumed applicable to the DS geometry. The importance of data validity is pointed out in the recently proposed European standard practice (4) where a unique approach is given to the problem of data validity in J_{IC} and J-R curve tests, in contrast with the corresponding ASTM standards, E813 and E1152, containing different validity requirements. The more relaxed requirements allowed by ASTM E813 for J_{IC} testing rise the important question of a tolerable degree of non-validity in J-Δa data when used to determine J_{IC} values. In this case it can be argued that the really important point is that the J-Δa data should be strictly valid only up to the point of definition of J_{IC}, while the other points after initiation must only be able to provide the basis for a correct backwards best-fit, down to J_{IC}. This point is very important for the miniature DS tests, as experience in tests on serviced ferritic steels often indicates that a J field can be demonstrated to exist up to J_{IC}, but the validity is lost after moderate amounts of crack extensions. Therefore the valid region of the J-Δa plots may be insufficient to determine J_{IC} from backwards extrapolation according to standard data reduction procedures, but is still adequate if sufficient J-Δa values in the initial portion of the diagrams are available, so that a J_{IC} estimate based on an interpolation of perfectly valid data can be followed. Of course if the specimen J-capacity is lost before J_{IC} value is reached, there is not much to do: this is the typical case when testing small DS specimens made of high-toughness steels. The more favourable situation for ferritic steels, especially in the serviced condition, is shown in fig. 2. DS specimens of a 1CrMoV steel were capable to provide valid J_{IC} data and even valid portions of J-R curves, in tests up to 300 °C; with 2.25Cr1Mo steels the validity region was smaller, allowing tests only up to room temperature where the J limit is generally close to J_{IC}. In any case, when testing ferritic steels care must be given in interpreting data in the brittle-ductile temperature transition regime: a relevant size effect may be present and this must be considered when using data from miniature specimens to predict the behaviour of real components.

Of course measuring accurate J-Δa data in the crack initiation region involves particular expertise, equipment and high costs. The difficulty is related to the required accuracy in measurements of crack length: here the Unloading Compliance (UC) method is totally inapplicable but even the PD method can suffer, for certain materials, of excessive "electric blunting line" problems. Therefore a coupled single-specimen/multi-specimen methodology is to be preferred, with an optimum compromise between data reliability and sample material consumption: three or four tests, all PD-instrumented, can be proposed from the authors' experience.

<u>Fatigue Crack Growth</u>. Miniature DS specimens can be conveniently

used, particularly on low alloy ferritic steels and high strength alloys, for which the specimens K-capacity is normally sufficient to get valid da/dN vs ΔK data from threshold up to a relatively large crack extension, so that the Paris' regime is normally entered. Since other methods (unloading compliance or visual) do not provide the necessary resolution in crack length measuring, the PD method should be used already in the precracking phase to closely control the final precrack extension and leave the maximum possible ligament for the real test. However this method implies a precise measure of a_0 after precracking, which means that the initial crack must be identified and measured on the fracture surface after the test. This is easy when the FCG test is run at high temperature, after precracking at room temperature; otherwise different marking techniques must be used, depending on temperature and material: heat tinting, infiltration, different R-ratio in precracking, the last being currently used by authors.

In FCG test on miniature DS specimens, small cyclic loads are also generally applied: due to the generally limited availability of material and to the lack of knowledge of its main mechanical properties (especially in the post-service conditions) a careful approach must be followed, starting the test at a very low cyclic load and rising it by small steps, until the crack begins propagating; a lower cyclic load is also useful to obtain valid FCG data up to large values of final crack length. Typical results showing the good agreement between FCG data from tests on large and miniature DS specimens are shown in fig. 3. However when deriving Paris' constants, attention must be put in using only the appropriate data, excluding the near-threshold data. For an adequate best-fit, if the data cover an insufficient span of the Paris regime, the tangent to the upper ΔK region must be used.

INTEGRITY ASSESSMENT

Structural integrity assessment is especially required for those components which may be "critical" in terms of safety and plant availability, as boiler drums, hot steam lines and headers, turbine and generator rotor forgings, turbine casings, end rings. The integrity assessment procedures must be tailored for each component, according to leading damage mechanisms and types of possible defects. Limiting the discussion to the case of turbine and generator rotor forgings, creep, fatigue (both high cycle and high temperature low cycle and thermal) and temper embrittlement are the most important damage phenomena, which, to an extent more or less depending on the specific component and on service conditions, set limits to the operating life. In the international as well as ENEL practice, the most important issue in the integrity assessment and residual life evaluation of rotor forgings is the risk of brittle catastrophic failure. Here the availability of the specific parameters of the actual material, mainly Fracture Mechanics data as K_{IC} or J_{IC} and da/dN or da/dt vs ΔK or C*, is felt to be necessary for any reliable evaluation. For this reason the use of the miniature specimens testing techniques has become common practice: miniature DS specimens for toughness and/or FCG tests are machined from small rings cut-off from the rotor body (fig. 4) in the most degraded regions or from axial trepans in coupling flanges of LP and generator rotors or radial trepans in the balance sections of HP/IP rotors. The analytical evaluations, for a complete post-service condition assessment performed with Fracture Mechanics criteria, are then integrated by information coming from non-destructive methods as metallurgical replicas, hardness measurements, dimensional checks.

CONCLUSIONS

A sophisticated version of the electric Potential Drop method was used on miniature DS specimens to monitor crack length and an indirect technique of load-point displacement measurement utilized in tests at the highest temperatures for which any existing clip-gage would have been inadequate. In terms of accuracy, the results from the sub-sized specimens were generally satisfactory. Only in FT tests under LEFM conditions, valid K_{Ic} values could not be obtained for most steels and EE toughness had to be considered: a better choice could have been the circumferentially notched cylindrical specimens recently considered for LEFM tests and which proved to give valid results in this conditions. The situation was better in FT tests under EPFM conditions, where the specimens generally retained sufficient J-capacity. In this latter case, some problems in applying existing standard procedures of data analysis to the peculiarities of the miniature specimens tests were experienced. K-capacity of specimens was sufficient for deriving well defined FCG curves.

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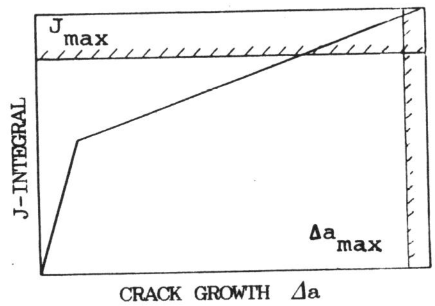

Figure 1 Validity requirements for J-Δa data

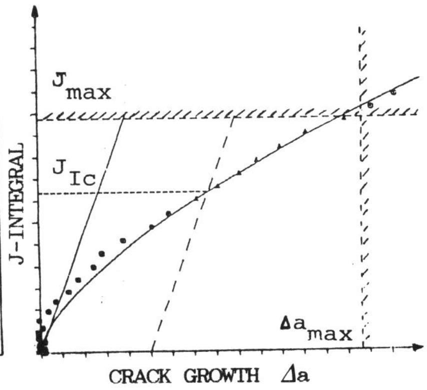

Figure 2 J-R curve from a DS specimen (ferritic steel)

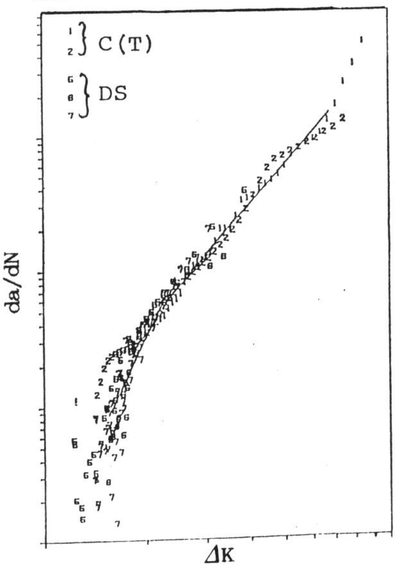

Figure 3 FCG data from C(T) and DS specimens

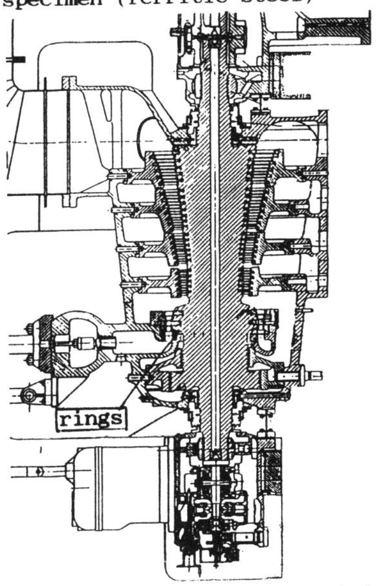

Figure 4 Example of material sampling from an LP rotor