THE "SMALL PUNCH" TECHNIQUE FOR EVALUATING QUASI NON-DESTRUCTIVELY THE MECHANICAL PROPERTIES OF STEELS

V. Bicego*, E. Lucon*, C. Sampietri*

The "Small Punch" (SP) technique uses tiny disks for deriving estimates of transition temperature ($FATT_{50}$), fracture toughness (J_{Ic}, K_{Ic}) and tensile properties (yield and tensile strength). It has proven useful for characterizing the mechanical properties of service-exposed components that have to be sampled almost non-destructively. The "traditional" approach is based on empirical correlations, established between the investigated properties and characteristic values derived from the SP test diagram. More recently, an "innovative" approach has been developed by EPRI (USA), based a more scientific and rigorous standpoint. Both points of view are considered and discussed in this paper, with some relevant results obtained on several classes of steels.

INTRODUCTION

The "Small Punch" (SP) technique uses tiny disk-shaped specimens (typical diameter 3 ÷ 10 mm, thickness ≈ 0.5 mm) for estimating mechanical properties of components which do not allow standard destructive material sampling: the specimen miniaturization, in this case, allows to avoid any post-sampling repairing, since the testpiece is entirely contained in the extra-thickness typically present in most plant components. The SP test has been applied for several years in Japan and US (1,2,3) on rotor and vessel steels. ENEL has more recently developed this technique by performing validation analyses based on comparison between $FATT_{50}$ and K_{Ic} data, measured in standard laboratory tests and estimated via the SP technique. In such analyses and in subsequent ones, based on a more recent approach proposed by EPRI, we have obviously operated on components which were available in a sufficient quantity for massive testpieces to be obtained: rotors (CrMoV, NiCrMo, NiCrMoV), pipings (2¼Cr1Mo), nozzle boxes (12Cr) and boiler drums (CuNi52Mo) of fossil-fuelled plants, all of which had previously been retired from service.

---

* ENEL Research, Diagnostics & Materials Dep. (before June 1998, CISE SpA) - SEGRATE (MI) - ITALY

THE TEST METHODOLOGY

A SP test basically consists in applying a compressive load, by means of a spherical-shaped puncher, to a disk-shaped micro-specimen, recording force and displacement data until final failure. The test is conducted in displacement control, with a slow rate (0.25 ÷ 0.5 mm/min) and tipically lasts a couple of minutes. Different geometries for the specimen and the puncher are being used throughout the world: the ENEL version is basically the same as the one adopted by EPRI (2), with puncher radius of 1.25 mm and disk-shaped specimen with 8 mm diameter and 0.5 mm thickness.

Two different versions of the SP technique presently exist:

- a "traditional" version, which consists in performing several tests at different temperatures, in order to obtain an estimate of the transition temperature ($FATT_{50}$) from the temperature/absorbed energy curve; moreover, by means of empirical correlations available in the literature, values of tensile properties and fracture toughness may be obtained as well;
- more recently, an "innovative" version has been developed in the US by *Failure Analysis Associates* (FAA) in the frame of research projects sponsored by EPRI (4,5); this approach combines experimental data and finite element calculations in order to derive, in a rigorous way, fracture toughness and true stress/true strain curve (with relevant parameters) of the material under investigation.

The "traditional" version of the SP technique

The ENEL test configuration consists of a servo-controlled hydraulic machine with vertical load axis, with the specimen moving upwards towards the puncher.

The area under the force/deflection curve up to the maximum force value represents the fracture energy. By performing several tests at different temperatures, a sigmoidal curve is obtained; the corresponding transition temperature (T_{SP}) can be empirically correlated (with fitting coefficients which depend on the class of steel) with the 50% shear fracture transition temperature in conventional impact tests ($FATT_{50}$). Given that the value of T_{SP} is well below room temperature, all SP tests have to be conducted with the test setup immersed in liquid nitrogen vapours.

Moreover, from a single force/deflection test diagram (usually at room temperature), several characteristic values of force are identified and eventually correlated, through semi-empirical algorhythms, with yield and tensile strength values and critical fracture toughness parameters.

The main problem associated with such empirical approaches is that they utilize fitting coefficients that have been calibrated over specific steels, typically American or Japanese; if one wants to develop autonomous correlations, an experimental campaign aimed at recalibrating literature relationships by comparing standard test results and SP predictions is therefore necessary. This has to be carried out using components that have been retired from service, and therefore allow the extraction of large-scale specimens as well as SP testpieces. Once the specific correlations have been derived and validated, the SP technique can be used for integrity assessments of in-service components and structures.

The "innovative" version of the SP technique

In order to compensate the empiricism and approximations previously mentioned, a different approach to the interpretation of the SP technique has been recently developed by FAA (*Failure Analysis Associates*) (4,5). This "innovative" version introduces the use of an extensometer for measuring specimen deflection and of a magnifying videocamera which records on tape the instant of crack initiation during the test.

The methodology includes finite element analysis of the SP specimen, aimed at iteratively deriving the Ramberg-Osgood parameters (K, n) of the true stress/true plastic strain curve ($\varepsilon_p = K\sigma^n$). Moreover, based on a theoretical fracture criterion, the value of fracture toughness K_{Ic} can be estimated when a critical value of the strain energy density (w_c) in the material is reached, independent of the geometrical configuration, and therefore identical for SP and C(T) specimens.

The experimental setup used in ENEL for performing "innovative" SP tests is shown schematically in Fig. 1; Fig.2 shows the flow diagram of the methodology for deriving tensile properties and fracture toughness.

EXPERIMENTAL RESULTS

An example of the correlation obtained, for one class of structural steel, between T_{SP} and conventional $FATT_{50}$ values is shown in Fig.3; comparative data collected allow to estimate $FATT_{50}$ values with a 95% confidence band of about ± 60 °C.

Figs. 4 and 5, on the other hand, show the error bands for the different mechanical properties as obtained from the SP technique, both in the "traditional" and "innovative" version, with respect to data measured on conventional specimens (round tensile bars, Compact Tension specimens) on several classes of structural steels. The tensile properties (yield strength, R_y, and tensile strength, R_m) appear consistently underestimated by the SP approach, both in the "traditional" (i.e. using literature correlations) and "innovative" versions (Fig. 4); nevertheless, the application of a correction coefficient appears feasible, based on a reasonably solid database of comparative tests.

As far as the evaluation of fracture toughness is concerned, there is a clear tendency to overestimate the measured critical values (Fig. 5), and the methodology needs some further refinement, both from the point of view of literature correlations and the "innovative" approach; an estimate of K_{Ic} can however be produced also by using the SP-calculated $FATT_{50}$ value, and making use of one of the several formulae available in the literature for correlating transition temperature with fracture toughness (6). Such estimated values are also reported in Fig. 5.

CONCLUSIONS

1. The $FATT_{50}$ values estimated with the “traditional” version of the SP technique are in good agreement with standard impact test results, having developed empirical correlations for the different classes of structural steels investigated.
2. The “traditional” SP technique, based on literature correlations, typically underestimates conventional tensile properties, although the possibility of standardizing *ad-hoc* correction factors seems feasible. The same seems to hold true for the estimated values calculated from the Ramberg-Osgood parameters (“innovative” version of the SP technique).
3. The evaluation of fracture toughness by means of “traditional” SP test seems to be totally unreliable, at least for the classes of structural steels that we are interested in; the most promising approach is presently based on the preliminary estimation of the $FATT_{50}$ value for the material under investigation.
4. The Ramberg-Osgood parameters of the true stress/true plastic strain curve are in satisfactory agreement with the corresponding properties measured in conventional tensile tests, at least for the preliminary analyses performed so far.
5. Fracture toughness values evaluated by means of the “innovative” version of the SP technique have yielded contradictory results so far; the methodology needs some further improvement, particularly in the very delicate stage of detecting fracture initiation in the video-recording of the SP test.

REFERENCES

(1) Mao, X. and Takahashi, H., J. of Nucl. Mat., Vol.150, 1987, pp.42-52.

(2) Foulds, J.R. and Jewett, C.W., "Miniature Specimen Test Technique for Estimating Toughness", EPRI Report GS-7526, Project 1957-10, 1991.

(3) Kameda, J. and Mao, X., J. of Mat. Sci., Vol.27, 1992, pp.983-989.

(4) Foulds, J.R., Woytowitz, P.J., Parnell, T.K. and Jewett, C.W., Vol.23, No.1, 1995, pp.3-10.

(5) Foulds, J.R., Wu, M., Srivastav, S. and Jewett, C.W., "Fracture and Tensile Properties of ASTM Cross-Comparison Exercise A533B Steel by Small Punch Testing", ASTM STP 1329, 1998, in publication.

(6) Bicego, V., Lucon, E. and Crudeli, R., to be published in Nucl. Eng. and Des., 1998.

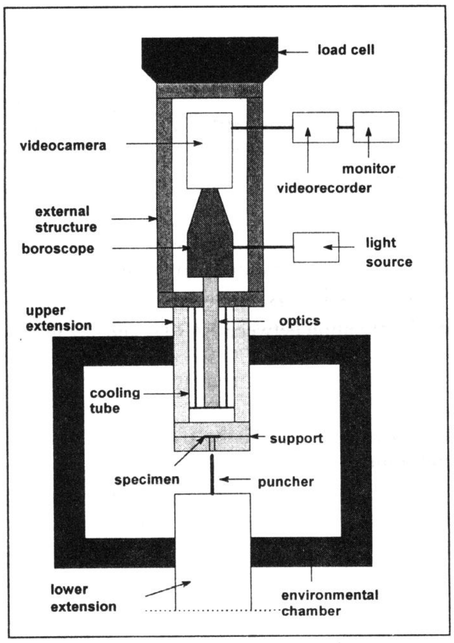

Figure 1 Test setup for performing “innovative” SP tests.

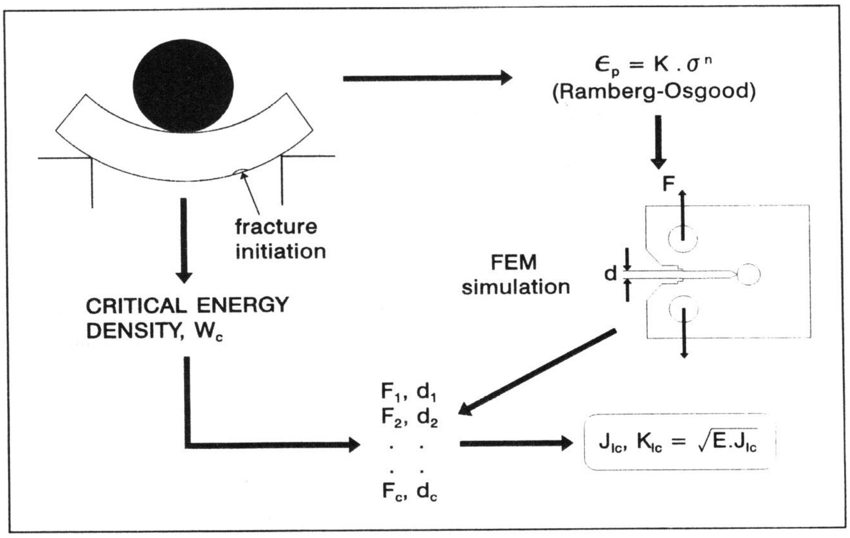

Figure 2 Scheme of the “innovative” version of the SP technique.

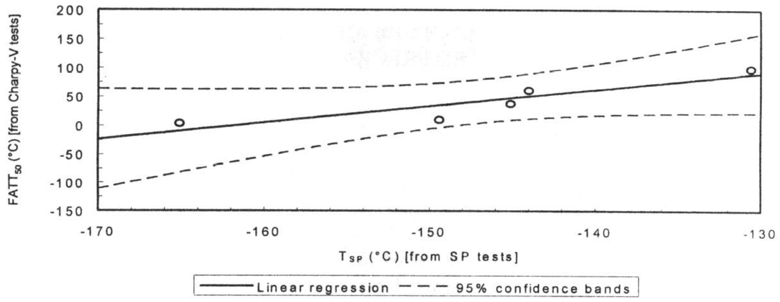

Figure 3 Example of correlation between FATT$_{50}$ and T$_{SP}$ for one of the steels investigated.

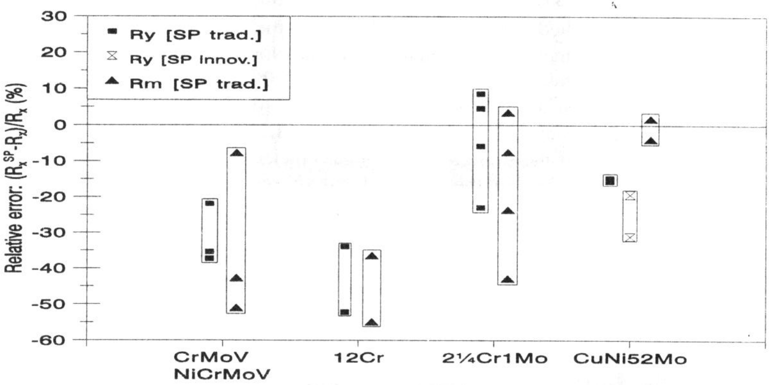

Figure 4 Errors obtained in estimating tensile properties with SP tests.

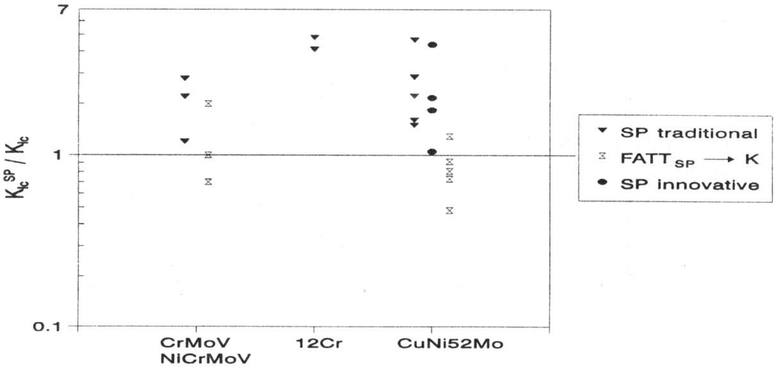

Figure 5 Errors obtained in estimating fracture toughness with SP tests.