NON DESTRUCTIVE EVALUATION OF MECHANICAL CHARACTERISTICS OF IN - SERVICE COMPONENTS' MATERIALS BY SMALL PUNCH TESTS

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ABSTRACT

Residual lifetime and/or structural integrity assessment of an electric power plant critical components requires the knowledge of an actual mechanical properties of the components' materials, because the material properties could be reduced throughout a service life by ageing. The use of standardised mechanical test technigues for determination of actual mechanical properties of a power plant component under operation can cause its considerable damage due to size of necessary testing material and following repairs by welding.

The need of a large amount of testing material can be eliminated by new advanced testing method based on „non destructive" sampling of a small amount of testing material from the component surface. The mechanical characteristics are then determined by Small Punch (SP) tests.

This paper describes the use of this advanced test technique for determination of tensile properties and fracture characteristics (FATT, J_{IC}) of materials.

INTRODUCTION

Residual lifetime and/or structural integrity assessment of an electric power plant critical components requires the knowledge of an actual mechanical properties of the components' materials because the material properties could be reduced throughout a service life by ageing. It is the process by which the physical and mechanical characteristics of the material change with time.

The risk of an abrupt failure of an operating component is a function of the size of the tolerable defect, which, in turn, is quantitatively related to the actual component material fracture toughness. For limiting this risk, particularly with low alloy steel components showing a transition behaviour, the operation of these components is simply constrained such that significant operating stresses are only permitted at temperatures exceeding the actual material FATT (Fracture Appearance Transition Temperature) [1]. Rotor pre-warming on a steam turbine start-up is a such constrained practice.

The use of standardised test technigues for determination of above mentioned mechanical properties of a power plant component under operation can cause its considerable damage due to the size of necessary testing material and following repairs by welding.

The need of a large amount of testing material can be eliminated by a new advanced testing method based on „non destructive" sampling of a small amount of testing material from the component surface. The mechanical characteristics are then determined by Small Punch (SP) tests [2].

This paper summarizes the procedures used for accurate estimation of tensile properties and fracture characteristics on the basis of Small Punch (SP) tests of disk-shaped test specimens 8 mm in diameter and 0,5 mm in thickness.

SAMPLING AND TEST TECHNIGUES

Sampling is carried out by VÍTKOVICE-Research and Development, Ltd. using Rolls-Royce SSam^{TM} – 2 scoop sampling machine (see Fig.1). The principle of the sampling is shown in Fig. 2. It employs a liquid cooled, hemispherical cup-shaped cutter with an abrasive

Fig.1 Rolls-Royce SSam^{TM} – 2 scoop sampling machine, [6]

coating at the spherical edge. It is rotated at a high speed and at the same time slowly feeds into the parent material removing a spherical cup 25 mm in diameter and 2.5 mm in thickness.

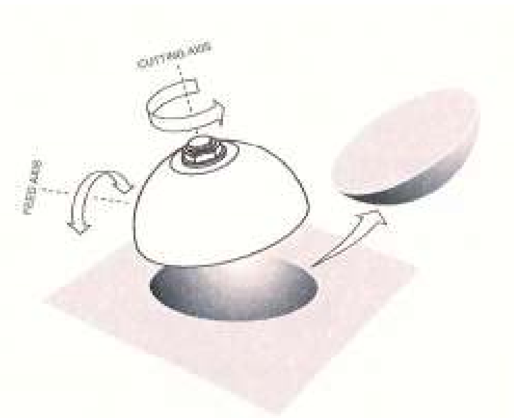

Fig.2 The principle of the sampling by SSam^{TM}-2

Fig. 3 shows a sample removed using this system together with SP test specimen blanks that have been subsequently machined from the miniature sample.

Fig. 3 Example of a miniature sample removed with the scoop system with SP test specimen blanks subsequently machined [6].

The following mechanical characteristics are accurately estimated by SP tests:

1. Yield stress, tensile strength and elongation at laboratory and higher (up to 400^{o}C) temperatures.
2. FATT.
3. Fracture toughness.

SMALL PUNCH TESTING PROCEDURE

The specimen clamped between lower and upper die is punched during the SP test with a hemispherical head to a failure (see Fig.4).

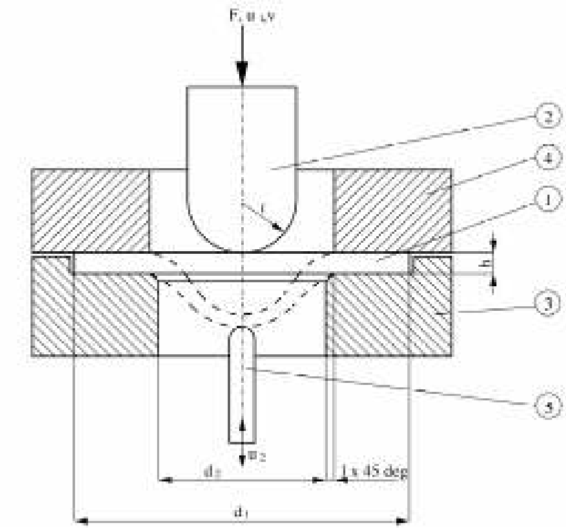

Fig.4 Cross-sectional scheme of the testing apparatus (1-specimen, 2-punch, 3-lower die, 4-upper die, 5-deflection measurement rod), [6].

The punch displacement and the force acting on the puncher are measured simultaneously. The result of the experiment is the load displacement curve (see Fig. 5).

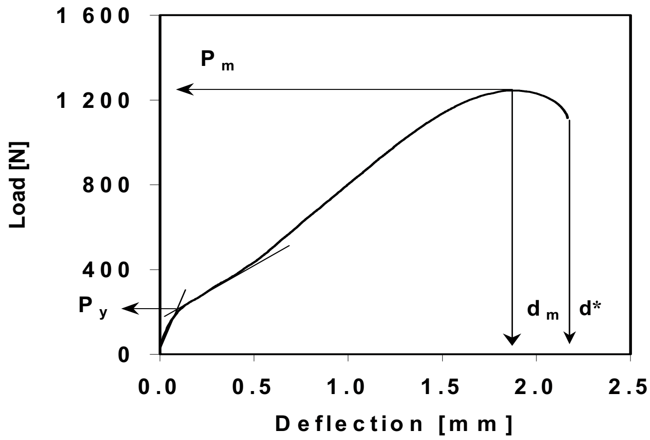

Fig. 5 Load displacement curve

The following characteristics of load displacement curve and failured test specimen are used for mechanical properties determination (estimation):

P_y [N] load characterizing the transition from linearity to the stage associated with the spread of the yield zone through the specimen thickness (plastic bending stage).

P_m [N] maximum load recorded during punch test

d_m [mm] displacement corresponding to P_m

d^* [mm] displacement corresponding to the specimen fracture

SP fracture energy E [J] energy obtained from the area under the load displacement curve up to the fracture load or displacement corresponding to the specimen fracture.

Effective fracture strain ε_f $\varepsilon_f = \ln(h_o/h_f)$ where h_o is the initial thickness of the specimen and h_f is the minimum thickness of the fractured specimen.

ESTIMATION OF TENSILE PROPERTIES USING SP TESTS

There are several equations proposed for the calculation of ultimate strength and yield stress from the parameters of SP tests [3,4,5]. As the nature of the SP load displacement curve varies with the punch radius, the hole diameter a the specimen thickness the tensile properties are determined from phenomenological correlations between SP and standardised tests results [1,2,6].

FATT ESTIMATION USING SP TESTS

On the basis of impact bend tests and SP tests results it has been shown that steels exhibiting a standard Charpy impact ductile to brittle fracture transition behaviour with decreasing test temperature also show a ductile to brittle energy transition behaviour with decreasing test temperature in a small punch test (see Fig.6). Transition temperature T_{SP}, measured in a series of small punch tests at test temperatures from -196° C to 25°C, is defined as a temperature at midpoint between maximum SP fracture energy and that at 200 N·mm.

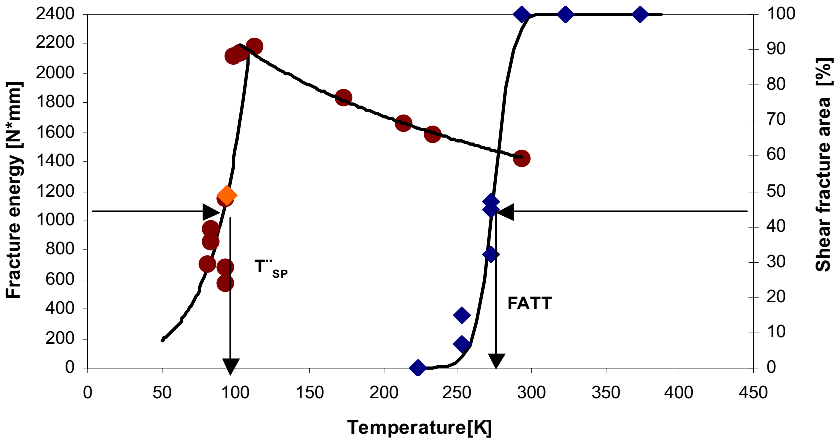

Fig.6 Transition behaviour observed in SP tests and impact bend tests results.

Typically, T_{SP} is shifted downward from Charpy FATT by an amount that is empirically established for a given steel (see Fig.6) . Previous papers [7-10] have described a simple relation between SP transition temperature T_{SP} (SP DBTT) and the FATT temperature determined from Charpy V-notch tests using the following linear equation at absolute temperature

$$T_{SP} = \alpha \,.\, FATT$$

where α is the correlation coefficient which has been found, for 12 grades of carbon and low alloy steels, to be $\alpha = 0{,}44$ [11].

ESTIMATION OF J_{IC} AT AMBIENT TEMPERATURE BY SP TESTS

The material fracture toughness is often unknown because it was never specified or measured, or because service conditions have resulted in its degradation to an unknown extent. Example of in-service degradation include temper embrittlement of steam turbine rotor low alloy steels exposed to elevated temperatures [1]. As the fracture behaviour of steels used in energy industry is possible to describe by elasto-plastic fracture mechanics the estimation of the material fracture toughness J_{IC} by SP tests has been based on empirical correlation between J_{IC} and effective fracture strain ε_f [1,2,6,14,15,16] given by equation

$$\mathbf{J_{IC} = K \cdot \varepsilon_f - J_0}$$

where K and J_0 are empirically determined constants and ε_f is the effective fracture strain. Mao et al. [14] suggest that K and J_0 are invariant, material independent constants. For low alloy ferritic steels K = 280 N/mm, J_0 = 50 N/mm. Effective fracture strain ε_f can be expressed by the following relation [6,15]:

$$\boldsymbol{\varepsilon_f = \ln(h_0/h_f)}$$

The procedure for a determination of the disk-shaped test specimen thickness h_f in the point of crack initiation is shown in Fig.8.

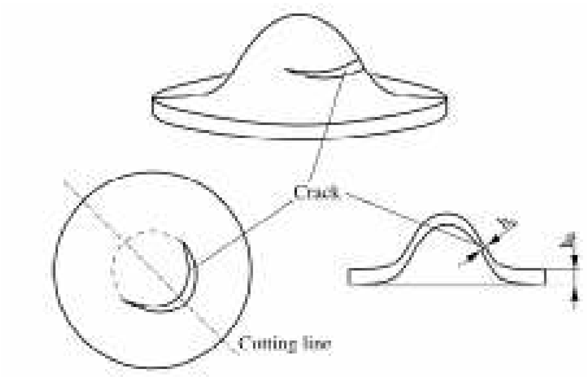

Fig.8 Procedure for determination of effective fracture strain ε_f, [6].

Effective fracture strain ε_f can be directly evaluated from the value of the displacement corresponding to the fracture d^*. The empirical relation

$$\boldsymbol{\varepsilon_f = \ln(h_0/h_f) = \beta \cdot (d^*/h_0)^x}$$

is assumed. Fig.9 shows a regresion line $\ln\ln(h_0/h_f)$ versus $\ln(d^*/h_0)$ obtained for SP tests at temperatures ranging from – 193°C to laboratory temperature. The values of thicknesses h_f are measured on metallographic samples (see Fig. 10)

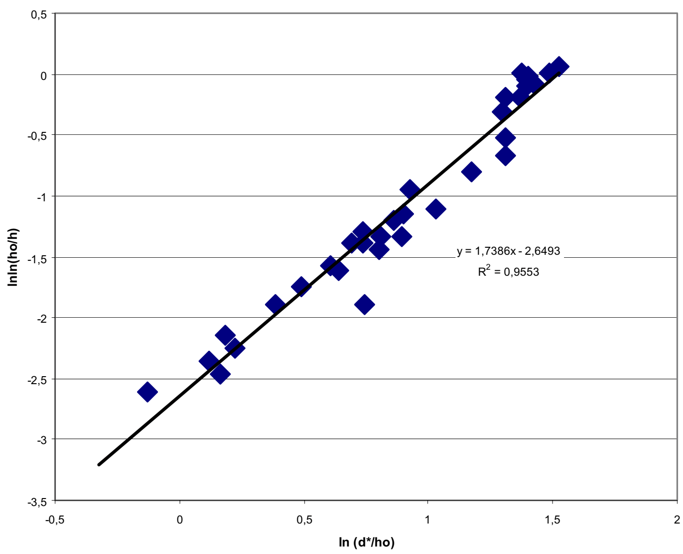

Fig. 9 Relationship between $\ln\ln(h_0/h_f)$ and $\ln(d^*/h_0)$ for the CrMoV rotor steel [13]

Fig.10 Metallographic sample od failured SP test specimen tested at -160°C,[13]

CONCLUSIONS

The Small Punch test technique provides at present time a vehicle for determination of actual tensile and fracture properties necessary for optimisation of operating procedures and inspection intervals as well as for repairs strategies and residual lifetime assessment.

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