THE EVALUATION OF MATERIALS PROPERTIES OF IN-SERVICE COMPONENTS BY SMALL PUNCH TESTS

Karel Matocha

Material & Metallurgical Research, Ltd.
Pohraniční 31, Ostrava, Czech Republic
tel.: +420 60 6750442, fax: +420 59 5953727
e-mail: karel.matocha@mmvyzkum.cz

Jaroslav Purmenský

74265 Rybí 155, Czech Republic
tel.: +420 60 2514201
e-mail: jaroslav.purmensky@seznam.cz

Abstract

Residual lifetimes and/or structural integrity assessments of critical components of mechanical plants and/or steel structures require the knowledge of 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 techniques for determination of actual mechanical properties of the components 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) Tests (SPT).

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

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.

Keywords: *material properties, small punch test, material ageing, nondestructive sampling, tensile and fracture properties*

1. Introduction

Residual lifetimes and/or structural integrity assessments of the critical components of mechanical plants and/or steel structures require 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 techniques for determination of above mentioned mechanical properties of the critical components 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 Tests (SPT) [2].

This paper summarizes the procedures used for accurate estimation of tensile properties and fracture characteristics using Small Punch Tests (SPT) of disc like test specimens 8 mm in diameter and 0.5 mm in thickness.

2. Sampling and test techniques

Material & Matallurgical Research, Ltd. owns 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 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. 1 Rolls-Royce SSam^{TM} – 2 scoop sampling machine [6]

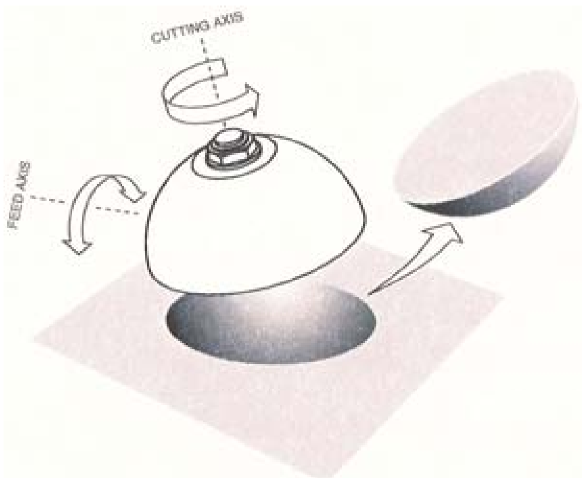

Fig. 2 The principle of the sampling by SSam^{TM}-2

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

The following mechanical characteristics can be estimated by SP tests:

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

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

3. 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).

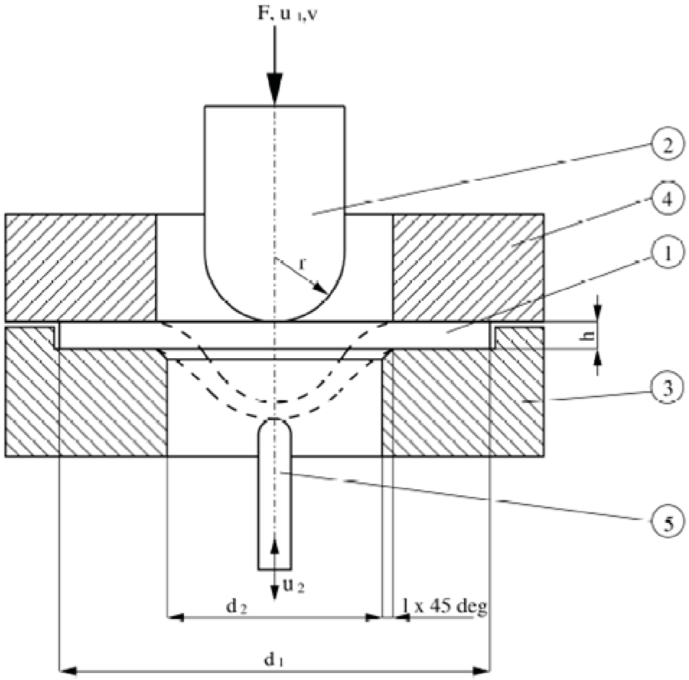

Fig. 4. Cross-sectional scheme of the testing apparatus (1 – specimen, 2 – punch, 3 – lower die, 4 – upper die, 5 – deflection measurement rod) [6]

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).

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.

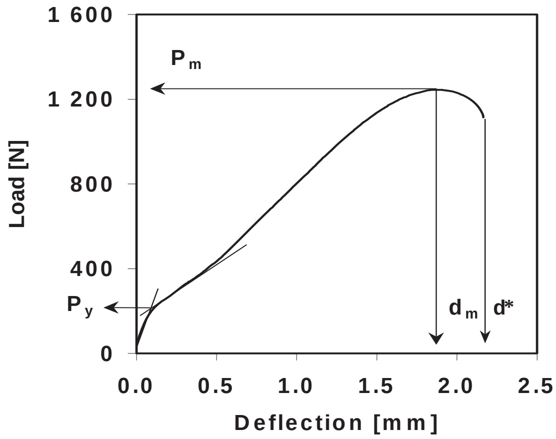

Fig. 5. Load displacement curve

4. 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 [3-5]. As the nature of the SP load displacement curve varies with the punch radius, the hole diameter and the specimen thickness the tensile properties are determined from phenomenological correlations between SP and standardised tests results [1, 2, 6].

5. 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.

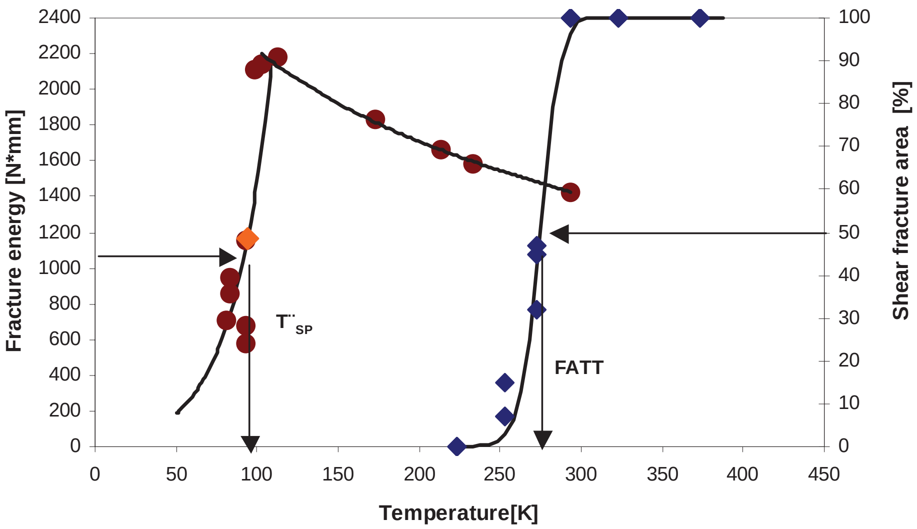

Fig. 6. Transition behaviour observed in SP tests and impact bend tests results

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 [7-11] 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:

$$T_{SP} = \alpha \,.\, \mathrm{FATT}, \tag{1}$$

where α is the correlation coefficient.

6. 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 structural steels at laboratory temperature is mostly 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, 13-15] given by equation

$$J_{IC} = K \cdot \varepsilon_f - J_0, \tag{2}$$

where K and J_0 are empirically determined constants and ε_f is the effective fracture strain. Mao et al. [13] 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, 13]:

$$\varepsilon_f = \ln(h_0/h_f). \tag{3}$$

The procedure for a determination of the disk-shaped test specimen thickness h_f in the point of crack initiation is shown in Fig. 7.

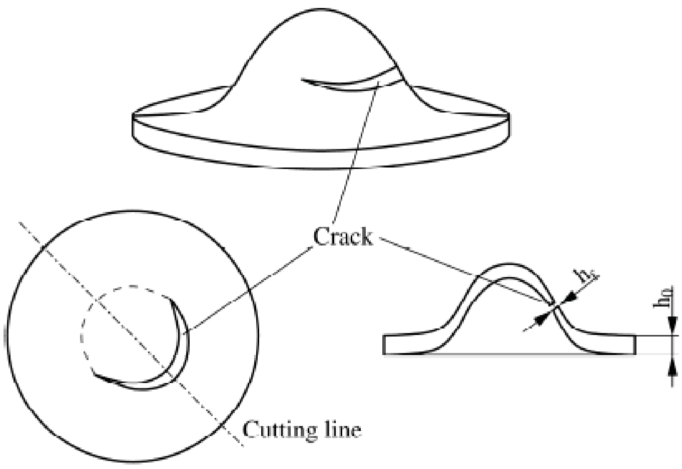

Fig. 7. Procedure for determination of effective fracture strain ε_f [6]

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

$$\varepsilon_f = \ln(h_0/h_f) = \beta \cdot (d^*/h_0)^x \tag{4}$$

is assumed. Fig. 8 shows a regression 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. 9).

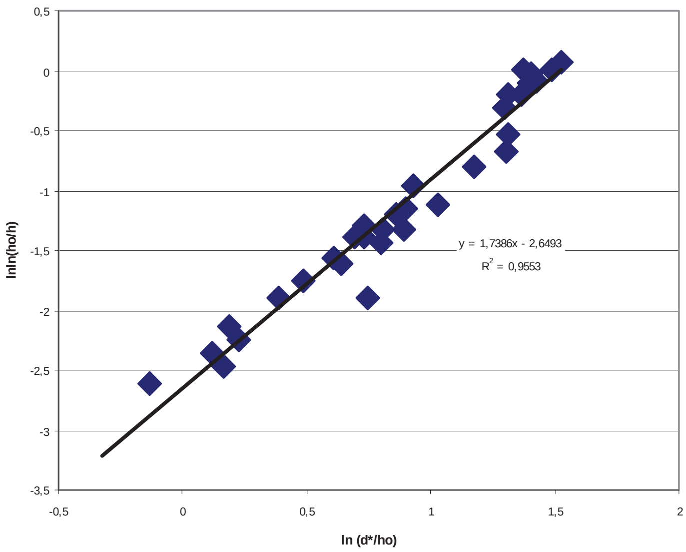

Fig. 8. Relationship between lnln(h_0/h_f) and ln(d^*/h_0) for the CrMoV rotor steel [12]

Fig. 9. Metallographic sample of failured SP test specimen tested at –160°C [12]

7. 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.

Acknowledgement

The author would like to express thanks to the ministry of Education, Youth and Sport of the Czech Republic for the financial support in the frame of the project MSM 2587080701.

References

[1] *Small Punch Testing for Fracture Toughness Measurement*, Final Report prepared for EPRI, TR-105130, Research Project 2426-38.
[2] Matocha, K., Purmenský, J., *Determination of actual mechanical properties of power plant components by small specimen testing technique*, KEMA Workshop Small Punch Testing, Arnhem 2005.

[3] Shah, P. K., Chatterjee, S., *Measurement of Tensile and Fracture Toughness Propertie Using Small Punch Test*, Proceeding of the International Conference & Exibition on Pressure Vessels and Piping OPE 2006-CHENNAI, Chennai, India 2006.

[4] Bicego, V., Lohr, R. D., *Mechanical testing on miniature specimens by the small punch method*, International Symposium on Materials Ageing and Life Management, Kalpakkam, India 2000.

[5] Onat, E. T., Haythornthwaite, R. M., *The load-carrying capacity of circular plates at large deflection*, Journal of Applied Mech., p. 46-55, 1956.

[6] *Small Punch Test Method for Metallic Materials*, CEN Workshop Agreement CWA 15627, December 2007.

[7] Ha, J. S., Fleury, E., *Small punch tests to estimate the mechanical properties of steels for steam power plant: II. Fracture toughness*, International Journal of Pressure Vessels and Piping, No. 75, pp. 707-713, 1998.

[8] Gai, X., Sato, Y. S., Kokawa, H., Ichikawa, K., *Ductile – brittle transition of steel electron beam weld metal in small punch test*, Science and Technology of Welding and Joining, Vol. 7, No. 4, p. 204, 2002.

[9] Purmenský, J., Matocha, K., *Determination of long-term material properties degradation using small specimen testing*, Proc. of 7th Informative and Training Symposium Diagnostic and Maintenance of Long Time Operated Power Equipment, Ustroň, Hotel Belweder, p. 97, 2005.

[10] Kander, L., Filip, M., Matocha, K., Purmenský, J., *Hodnocení vlastností kotlového tělesa z materiálu 11416.1 po dlouhodobém provozu metodou malých vzorků*, Kotle a energetická zařízení, Brno, 2006.

[11] Filip, M., S*tanovení mechanických vlastností a FATT z odlitku VT RZV-RV1 z materiálu 422740.6*. Zpráva VÍTKOVICE-Výzkum a vývoj, spol. s r.o., T-46/2006, Ostrava, Prosinec 2006.

[12] Matocha, K., Filip, M., Purmenský, J., Kander, L., *Measurement of Tensile and Fracture Toughness Properties of Material Samples Taken from Steam Turbine Rotor in Lodž Power Plant Using Small Punch Test*. Report of VÍTKOVICE-Researchand Development, Ltd., T-24/2006, September 2006.

[13] Mao, X., Saito, M., Takahashi, H., *Small Punch Test to Predict Ductile Fracture Toughness* J_{IC} *and Brittle Fracture Toughness* K_{IC}, Scripta Metallurgica et Materialia, Vol. 25, No. 11, pp. 2481-2485, 1991.

[14] Misawa, T., Nagata, S., Aoki, N., Ishizaka, J., Hamaguchi, Y., *Fracture Toughness Evaluation of Fusion Reactor Structural Steels at Low Temperatures by Small Punch Tests*, Journal of Nuclear Materials, Vol. 169, pp. 225-232, 1989.

[15] Mao, X., Shoji, T., Takahashi, H., *Characterization of Fracture Behaviour in Small Punch Test by Combined Recrystallization-Etch Method and Rigid Plastic Analysis*, J. Testing and Evaluation, Vol. 15, p. 30, 1987.