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

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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, JIC) 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 & Metallurgical Research, Ltd. owns Rolls-Royce SSam™ – 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.

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. 1 Rolls-Royce SSam™ – 2 scoop sampling machine [6]

Fig. 2 The principle of the sampling by SSam™-2
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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).

![Cross-sectional scheme of the testing apparatus](image)

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 failed test specimen are used for mechanical properties determination (estimation):

- $P_\gamma$ [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 $\varepsilon_f = \ln(h_o/h_f)$ where $h_o$ is the initial thickness of the specimen and $h_f$ is the minimum thickness of the fractured specimen.

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. 5. Load displacement curve](image)

![Fig. 6. Transition behaviour observed in SP tests and impact bend tests results](image)
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:

$$T_{SP} = \alpha \cdot \text{FATT}, \quad (1)$$

where $\alpha$ 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 $\varepsilon_f$ [1, 2, 6, 13-15] given by equation

$$J_{IC} = K \cdot \varepsilon_f - J_0, \quad (2)$$

where $K$ and $J_0$ are empirically determined constants and $\varepsilon_f$ 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 $\varepsilon_f$ can be expressed by the following relation [6, 13]:

$$\varepsilon_f = \ln(h_0/h_f). \quad (3)$$

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.

![Procedure for determination of effective fracture strain $\varepsilon_f$](image)

**Fig. 7. Procedure for determination of effective fracture strain $\varepsilon_f$ [6]**

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

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

is assumed. Fig. 8 shows a regression line $\ln(h_0/h_f)$ versus $\ln(d^*/h_0)$ obtained for SP tests at temperatures ranging from $-193^\circ C$ to laboratory temperature. The values of thicknesses $h_f$ are measured on metallographic samples (see Fig. 9).
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.

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