Small Punch Test Application to Material Properties Evolution Determination*

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Abstract

The current paper deals with the ability of the Small Punch Test [SPT] to detect material behaviour changes. The authors investigated two experimental materials with a range of mechanical properties. The different material properties of the experimental materials were obtained by heat treatment, simulating material property changes due to service conditions. The ability of SPT to detect such changes was investigated on the basis of tensile and fracture toughness properties. In order to be able to perform such an investigation, standard tensile tests and fracture toughness tests were performed for reference. A wide range of tensile strengths, ranging from 700 to 2000 MPa, and fracture toughness values covering the brittle-to-ductile region from 90 to 350 MPa.m^{0.5} were utilized for the method sensitivity assessment. The results of standard tests are compared with SPT results and their applicability is evaluated.

Key words: Small Punch Test, Fracture Toughness, Brittle Fracture, Ductile Fracture, Tensile Test

1. Introduction

There are increasing demands for the integrity assessment of important structures over the course of their service life. Fracture mechanics has attained high significance in establishing the ultimate load limitations and in assessing the integrity of many engineering structures of multifarious types. The fracture mechanics-based integrity assessment procedure for components requires fracture toughness properties of the materials which in many cases are difficult to obtain, due to lack of experimental material. For this reason non-destructive techniques are being developed, as well as testing methods using mini-samples to enable conversion of test results into conventional parameters such as tensile properties and fracture toughness parameters. One of the methods of the highest interest is the Small Punch Test (SPT).

The SPT method uses small disc-shaped samples with usual dimensions of 8mm diameter and 0.5mm thickness. The test itself is a very simple penetration of a hard ball into the test sample while the applied force and ball displacement are measured, either at room temperature or at non-ambient temperature. But problems may arise in the evaluation of the tests. Many procedures have been proposed for correlations between SPT and a variety of mechanical test results including tensile, Charpy impact, transition temperature determinations, fracture toughness evaluation, etc.

Some proposed correlations of SPT with tensile test properties and fracture toughness are given in publications [1-10]. These correlations are not generally valid for all materials: therefore in the current paper the correlations are re-assessed and directly applied to the

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materials investigated. Hence the performance of SPT for conventional properties evaluation is evaluated.

2. Experimental Materials

The experimental materials used were two steels. The first is an experimental grade of low carbon steel, designated as Steel 1. The second is Czech Standard grade 16 343 (whose international equivalent is 34CrNiMo6). Steel 1 was investigated in six different states (as-received, and annealed at 250, 350, 440, 500 and 620°C) produced from one material block. Steel 16 343 was tested in as-received condition exhibiting upper shelf behaviour at room temperature, and in the quenched state exhibiting brittle behaviour at room temperature. Tests on steel 16 343 in the as-received condition were performed in both the longitudinal and transverse directions of the rolled bar. The material tensile properties are summarized in **Table 1**.

Table 1. Tensile properties

Material	State	$R_{p0,2}/R_{eH}$	R_m	A_5	Z
		[MPa]	[MPa]	[%]	[%]
Steel 1	Original	1144,8	1252,6	14,2	70,3
	250	1168,5	1365,6	13,6	67,1
	350	1166,6	1285,6	14,1	69,4
	440	981,1	1022,1	16,9	70,9
	500	816,0	863,3	17,5	71,2
	620	699,9	734,0	21,4	74,1
34CrNiMo6	Longitudinal	921,3	1050,4	17,5	63,4
	Transversal	952,6	1053,3	15,7	60,0
	Quench	1219,6	1965,0	10,7	38,8

3. Fracture toughness tests

The fracture toughness tests were performed on three point bend specimens of thickness B 12.5mm. The crosshead speed during the tests was 2mm/min. The evaluation was performed according to ASTM E1820. Samples were machined then fatigue pre-cracked with the final stress intensity factor of about $20 \text{ MPa}\cdot\text{m}^{1/2}$. Test pieces were side-grooved after pre-cracking and subsequently tested using the multiple specimen method. Crack lengths after testing were measured by digital image processing and stress intensity factor or J-integral was determined. At least three samples were tested for each material state. Tests were performed at room temperature, and in the case of steel 1 in the as-received condition, tests at -20°C were also performed. The results of the fracture toughness test are summarized in **Table 2**. Some results did not fulfill the E1820 requirements for size-independent fracture toughness: these tests are denoted as J_Q/K_Q in the results table.

Table 2. Fracture toughness values

Material	State	Temperature °C	J_{IC}, J_Q kN.m	K_{IC}, K_Q MPa.m ^{0,5}
Steel 1	Original	20	----	127,1
	Original	-20	----	105,5
	250	20	----	112,6
	350	20	----	127,0
	440	20	253,5	241,9
	500	20	383,0	297,3
	620	20	517,0	345,4
34CrNiMo6	Long	20	286,8	257,3
	Trans	20	189,9	209,3
	Quenched	20	101,3	92,2

4. Small Punch Tests

Small punch tests were performed in a servo-hydraulic testing system of 10kN capacity using the testing fixture shown to **Fig. 1**. Dimensions of the fixture can be found in **Table 3**.

Fig. 1. Small punch test fixture

Table 3. Dimensions of SPT fixture

h_0	D	R	r	d_h
0,5	8,0	1,25	0,5	4,0

The SPT sample preparation was as follows: first a disc of thickness about 1mm was cut using coolant. Next the sample was ground from 1mm thickness down to 0.6mm on metallographic grinding discs while mounted in a specially-designed holder. The last 0.1mm of sample thickness was removed by diamond polishing. During the preparation process the sample was regularly turned to ensure that both faces experienced similar conditions. Tests were performed at room temperature and at -20°C. The tests at -20°C were performed in a cooling chamber using liquid nitrogen vapour. The crosshead speed during SPT tests was 1mm/min. Force-displacement curves obtained for all materials are shown in **Figs. 2** and **3**.

Fig. 2. SPT records - Steel 1

Fig. 3. SPT records – 34CrNiMo6

5. SPT tests evaluation – tensile properties

The records obtained were firstly used for the evaluation of the tensile properties of the materials investigated. To accomplish this, distinctive points from the records were determined according to **Fig. 4** and subsequently the yield stresses and the tensile strengths were evaluated. Graphical representations of the results obtained in comparison with standard tensile test results are shown in **Figs. 5** and **6**. It is clear that linear trends can be found for yield stress and tensile strength by comparison to tensile tests results.

Fig. 4. Scheme of distinctive points determination from SPT record [5]

Fig. 5. Tensile Yield stress versus normalized F_e from SPT

Fig. 6. Tensile strength versus normalized yielding force from SPT

Various procedures for fracture toughness evaluation from SPT have been published in [1-10]. In the case of brittle fracture the following relationship is recommended [3]:

$$K_{IC} = C \cdot [\sigma_{JSP}]^{2/3} \quad (1)$$

$$\sigma_{JSP} = 130 (P_{max} / h_0^2) - 320 \quad (2)$$

where P_{max} is the force at unstable crack propagation and h_0 is the initial sample thickness. C is an empirically determined constant [5].

On the basis of the current results C was determined to be 1.029. The results of fracture toughness evaluated with this constant were compared with fracture toughness data evaluated from standard tests, and the results are summarized in Table 4. A graphical representation of the obtained results is shown in Fig. 10.

In the case of upper shelf behaviour the following relation is widely used [5]:

$$J_{IC} = K \cdot \varepsilon_f - J_0 \quad (3)$$

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

where ε_f is fracture strain, h_0 initial sample thickness, h_f sample thickness in the crack region, d^* is displacement at sample fracture and β , x , K and J_0 are empirically determined constants.

There are two possibilities of ε_f determination as can be seen from Eq. (4). The first is to determine the fracture strain by measurement of the sample thickness after fracture in the crack region according to Fig. 7. The second possibility is its determination from test records by using the displacement at fracture (d^*). Comparison of the fracture strain determined by both methods is shown in Fig. 8 where it can be seen that there is a linear trend between fracture strains ε_f obtained by both methods. On the basis of this finding, it is concluded that ε_f can be determined directly from the test records without the need for additional experimental effort. The fracture strains obtained from the graphs were used for further evaluations.

a) Steel 1 – annealed at 500°C

b) 34 CrNiMo6 – as delivered - longitudinal

Fig. 7. Determination of ϵ_f on the basis of optical measurements

Fig. 8. Comparison of ϵ_f determined from fracture faces and from calculation

Fig. 9. Determination of correlation constants for fracture toughness determination

The values of the constants for the current materials in Eq. (3) were determined from Fig. 9.; $K=354,4\text{kN/m}$ and $J_0=51,4\text{kN/m}$. The constants in Eq. (4) were determined iteratively by searching the best agreement between results of standard tests and SPT; $\beta=0,111$, $\alpha=1,69$.

The fracture toughness values obtained from SPT tests and from standard tests are summarized in **Table 4**. A graphical representation of the data is shown in **Fig. 10** where $\pm 15\%$ error boundaries are shown.

Table 4. Results of fracture toughness evaluation

Material	State	Temperature °C	J_{IC_SPT} kN.m	J_{IC}, J_Q kN.m	K_{IC_SPT} MPa.m ^{0.5}	K_{IC}, K_Q MPa.m ^{0.5}
Steel 1	Original	20	----	----	113,7	127,1
	Original	-20	----	----	115,5	105,5
	250	20	----	----	120,3	112,6
	350	20	----	----	114,2	127,0
	440	20	354,4	253,5	286,0	241,9
	500	20	386,2	383	298,5	297,3
34CrNiMo6	620	20	410,9	517	307,9	345,4
	Long	20	284,7	286,8	256,3	257,3
	Trans	20	223,2	189,9	227,0	209,3
	Quenched	20	----	----	101,3	92,2

Fig. 10. Graphical summarization of fracture toughness evaluation results

7. Discussion of Results

Evaluation of the tensile test data shows very good agreement between the small punch test data and the results obtained by standard tensile tests. These results strongly support the application of small punch tests for tensile property evaluation for the steels investigated under all the conditions considered.

The fracture toughness tests of experimental material on the lower and the upper shelf regions were performed together with small punch tests. Separated evaluations were carried out for both regions.

In the lower shelf region, evaluation of fracture toughness from SPT was based on **Eqs. (1) and (2)**. In this evaluation one constant has to be found only. The constant for the current data set was obtained and good agreement between reference values and SPT values was found.

In the case of stable crack extension behaviour is fracture toughness evaluated according to **Eqs. (3) and (4)** from SPT. In this case the evaluation is using fracture strain. The fracture strain can be determined on the basis of physical measurements of sample after the tests, or from obtained test records. Experimental measurement of the fracture strain requires additional effort, while direct evaluation from the graph is simple and can be automated. Analyze of current results pointed out possibility of the use of fracture strain

determined from graph. With the use of this determination fracture toughness for the upper shelf behaviour was evaluated. Results of determined fracture toughness data are summarized in **Fig. 10**, where very good agreement of SPT based results with those obtained from standard tests is confirmed. This finding is very positive confirmation of the applicability of SPT to fracture toughness determination.

8. Conclusions

Small punch tests (SPT) applicability to material properties change evaluation was investigated here. Altogether, two materials in 10 states were investigated for sensitivity assessment of the SPT method. Tensile tests properties and fracture toughness properties were observed.

Tensile tests evaluation shown very good agreement between small punch test data and results obtained by standard tensile tests. These results prove possibility of application of small punch tests for tensile properties evaluation the material behaviour change description.

Fracture toughness tests of the materials investigated exhibited very good results in comparison with fracture toughness data from standard tests. The assessment of the SPT tests pointed out following results:

- Determination of lower shelf fracture toughness and upper shelf fracture toughness has to be done separately.
- In the case of upper shelf behaviour, where the evaluation is based on fracture strain, the fracture strain can be evaluated from SPT record directly without need for additional measurements.
- Very good agreement between reference values and SPT results is found.

SPT is potentially very powerful method in cases when limited amount of material is available e.g. for the residual life evaluation of in service components. Attention has to be paid if correct parameters and correct evaluation procedure is used for the material investigated.

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