THE EFFECT OF STIFFNESS OF THE LOADING SYSTEM ON DETERMINATION OF TENSILE CHARACTERISTICS FROM THE RESULTS OF SMALL PUNCH TESTS

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Abstract
The assessment of the residual lifetime of critical components of industrial plants requires the knowledge of mechanical properties prior to operation, respecting all technological operations realized throughout the manufacture of the component, and the knowledge of mechanical properties after actual time of operation (actual mechanical properties). The conventional mechanical tests require relatively large volume of testing material and extracting it from an operating component can impair its integrity. The need for evaluating the actual mechanical properties by direct testing method has led to development of innovative techniques based on miniaturized specimens. Among these, a technique called the Small Punch (SP) test has emerged as a promising candidate. It enables measurement of the realistic material properties at the critical locations in the component both prior and after long-term operation. Yield stress and tensile strength at ambient temperature are determined from empirical correlations between SP and standardized test results. In the present paper the empirical correlations obtained in two laboratories for determination of yield stress and tensile strength of low alloy steel of type 14MoV6-3 in as received state from the results of SP tests are compared and the differences obtained are discussed. The results obtained demonstrate the significance of loading system stiffness on the results of SP tests at laboratory temperature.

Keywords: SP test, load-displacement curve, stiffness of the testing machine, stiffness of the testing rig, yield stress, tensile strength

1 Introduction

The residual lifetime assessment and potential for possible failure of in-service components is a critical issue in the safety and reliability analysis of industrial plants, in particular for operating power stations and petrochemical plants which are approaching the end of their design lives [1]. The conventional mechanical tests require relatively large volume of testing material and extracting it from an operating component can impair its integrity. In such situations, mechanical tests based on small specimens test techniques are efficient for characterizing the mechanical properties of components. A promising candidate based on very limited amount of testing

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material to be sampled is the Small Punch Test Technique. It is mechanical testing method used at the present time to obtain tensile, fracture and creep characteristics with the specimens of disc shape 0.25–0.5 mm thick and 8–10 mm diameter. In 2007 CWA 15627 “Small Punch Test method for Metallic Materials” [2] was issued by CEN (European Committee for Standardization). In 2012 the solution of bilateral project, focused on the comparison of Codes of Practice for determination of tensile and fracture characteristics by SP tests between EU and China, was initiated in the frame of Czech-Chinese Scientific and Technological Cooperation. The participants of the project were Material & Metallurgical Research Ltd. (MMR), Ostrava, Czech Republic and School of Mechanical Engineering, East China University of Science and Technology, Shanghai, China. Both European Code of Practice [2] and Chinese Code of Practice [3, 4] give guidance on the procedure to be followed when carrying out Small Punch tests aimed at evaluation of tensile and fracture characteristics of the metallic materials. On the basis of common experimental programme, realized in both laboratories on low alloy steel of 14MoV6-3 type in as-received state and after long-term operation at 540°C, the database of results of standardized tensile tests, impact tests, fracture toughness tests and the SP tests results in temperature range -193°C - +20°C was obtained.

In the present paper the empirical correlations obtained in both laboratories for determination of yield stress and tensile strength at ambient temperature from the results of SP tests are compared and the differences obtained are discussed.

2 Experimental material and methods

A pipe ø 457 x 28 mm in the as-received state made of low alloy steel of 14MoV6-3 type was used as the testing material. Chemical composition of the testing materials is shown in **Table 1**.

Table 1 Control chemical analysis of the tube in the as-received state

C	Mn	Si	S	P	Cr	Mo	Ni	V	Al	N	J	X
mas. %											-	ppm
0.12	0.57	0.19	0.005	0.009	0.57	0.52	0.08	0.32	0.020	0.013	114	12.0

Metallurgical quality of the testing material was expressed by BRUSCATO factor X [5]:

$$X= (10.P+5.Sb +4.Sn+As)/100 \quad (1.)$$

and J factor [6]:

$$J = (Si + Mn) x (P + Sn) x 10^4 \quad (2.)$$

Table 2 Selected regimes of heat treatment of testing segments

HT1	940°C/1 hour/water + 720°C/2 hours/air
HT2	940°C/1 hour/furnace +720°C/2 hours/air
HT3	940°C/ 1 hour/oil + 720°C/2 hours/air
HT4	940°C/1 hour/air + 720°C/2 hours/air
HT5	940°C/1 hour/water + 700°C/2 hours/air
HT6	940°C/1 hour/air + 740°C/2 hours/air
HT7	940°C/1 hour/oil + 740°C/160 min./air

Segments of the size 405 x 70 mm, cut from the pipe, were heat treated by 7 different regimes HT1 to HT7 (see **Table 2**) to obtain significantly different yield stresses and tensile strengths. In

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order to compare the effect of testing conditions and testing rigs, standardized round bar tensile test specimens 8 mm in diameter, oriented in longitudinal direction and semi-products of SP disc specimens of 8 mm and 10 mm in diameter oriented in R-L direction were manufactured in mechanical workshop of MMR for both laboratories.

3 Results

3.1 Tensile tests

Tensile tests at ambient temperature were carried out in the laboratory MMR on servo-hydraulic testing machine MTS 100 kN under stroke control at the rate 1.5 mm/min. The same tests were carried out at the School of Mechanical Engineering (SME) in Shanghai on servo-hydraulic testing machine Instron 8800 at the rate 1.0 mm/min. Results obtained in both laboratories are summarized in **Table 3**. Values listed in the table are the average values of three measurements. The results obtained show a good agreement between the average values of yield stress, tensile strength, elongation and reduction of area determined in both laboratories.

Table 3 Comparison of tensile test results at ambient temperature carried out in both laboratories

Heat treatment	Yield stress [MPa]		Tensile strength [MPa]		Elongation [%]		Reduction of area [%]	
	MMR	SME	MMR	SME	MMR	SME	MMR	SME
As-received	350	375	492	505	31.8	31.2	81	79
HT1	664	646	725	712	24.7	21.8	78	81
HT2	319	323	462	457	25.6	38.3	78	79
HT3	616	607	701	694	25.5	25.4	77	80
HT4	403	409	536	535	30.3	29.1	83	81
HT5	426	435	554	563	30.0	26.2	81	81
HT6	384	-	519	-	33.5	-	80	-
HT7	541	-	638	-	-	-	-	-

3.2 Small Punch tests

Test specimen preparation was carried out in each laboratory in accordance with the Codes [2, 3]. Disc specimens 8 mm in diameter and 0.5±0.005 mm in thickness were used in MMR, disc specimens 10 mm in diameter and 0.5±0.005 mm in thickness were used in Shanghai University. The screw-driven testing machines were used in both laboratories (Lab Test 5.10) with a capacity of 5 kN at MMR, CSS 44000 with a capacity of 20 kN at SME. The testing rigs (see **Fig.1**) with the lower die hole diameter D = 4 mm, puncher with punch tip diameter 2.5 mm (at MMR) and steel ball with the hardness greater than 60 HRC (at SME) were used for SP tests in the temperature range -193°C to ambient temperature.

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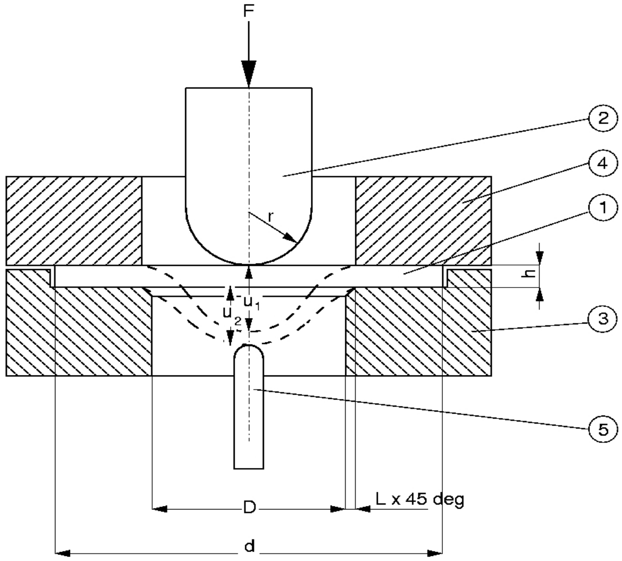

Fig. 1 Cross - sectional scheme of the testing rig (1–specimen, 2–punch, 3–receiving die, 4–clamping die, 5– deflection measurement rod).

SP tests at both laboratories were carried out under crosshead control at crosshead speed of 1.5 mm/min.

The objective of the test is to produce a load-displacement (punch displacement, crosshead displacement) record (see **Fig. 2**) and/or load-specimen deflection record, which contains information about the elastic-plastic deformation and strength properties of the material.

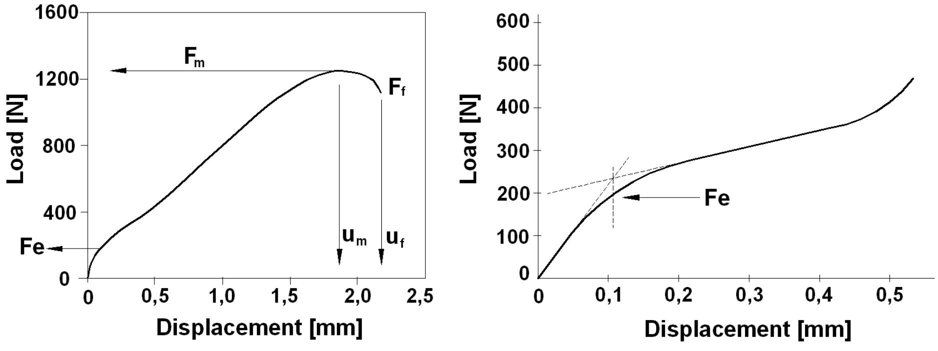

Fig. 2 Load-displacement curve recorded during a small punch test of a ductile material

The following SP related parameters are used for determination of yield stress and tensile strength from such a load-displacement curve:

F_m [N] - maximum load recorded during SP test,

F_e [N] - load characterising the transition from linearity to the stage associated with the spread of a yield zone through the specimen thickness. It is determined according to both Codes by two tangents method (see **Fig. 1**),

u_m [mm] - displacement corresponding to the maximum load F_m,

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The load-displacement curves obtained can be utilised to derive empirical correlations between SP and standardised test results [1, 7-11] or they can be analysed in terms of elastic-plastic finite element methods [12-14]. **Fig. 3** shows the comparison of empirical correlations for determination of yield stress at ambient temperature for 14MoV6-3 steel in as-received state. Empirical correlations were expressed as the dependences of yield stress on parameter $F_e/(h_0)^2$ [15-17], where F_e is the load characterizing the transition from linearity to the stage associated with the spread of the yield zone through the specimen thickness (see Fig. 1), because it was proved that the parameter $F_e/(h_0)^2$ eliminated any difference in disc specimen thicknesses on load F_e [1, 18].

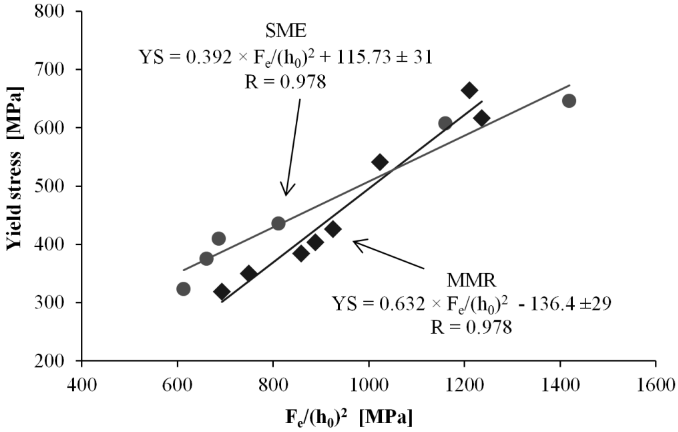

Fig. 3 Comparison of empirical correlations for yield stress obtained at MMR and SME for 14MoV6-3 steel in the as-received state

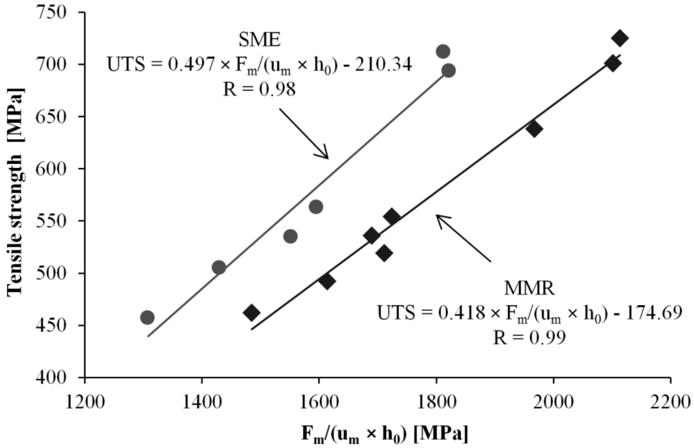

Fig. 4 Comparison of empirical correlations for ultimate tensile strength obtained at MMR and SME for 14MoV6-3 steel in the as-received state

Fig. 4 shows the comparison of empirical correlations for determination of tensile strength at ambient temperature for 14MoV6-3 steel in as-received state. Empirical correlations were

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expressed as the dependences of tensile strength on parameter $F_m/(u_m \cdot h_0)$ where F_m is the maximum load recorded during SP test and u_m is the displacement corresponding to the maximum load F_m. In this case the parameter $F_m/(u_m \cdot h_0)$ is used to eliminate any differences in disc specimen thicknesses on F_m and u_m [1, 18].

4 Discussion

It is evident that mainly the correlations for a determination of ultimate tensile strength are significantly different in both laboratories. To explain the significant differences in empirical correlations for determination of tensile strength from the results of SP tests the values of maximum load during SP test F_m and displacement corresponding to maximum load u_m obtained in both laboratories are summarized in **Table 4**. Values listed in the table are the average of three SP tests.

Table 4 Comparison of F_m and u_m obtained in both laboratories during SP tests at ambient temperature

Testing machine	Testing rig	F_m [N]	u_m [mm]
CSS 44000	SME Shanghai	1355	1.845
	MMR, Ltd.	1446	1.857
Lab Test 5.10	MMR, Ltd.	1450	2.005

Fig. 5 shows the differences in stiffness of test fixtures used for penetration tests carried out in laboratory of SME on servo-mechanical testing machine CSS 44 000.

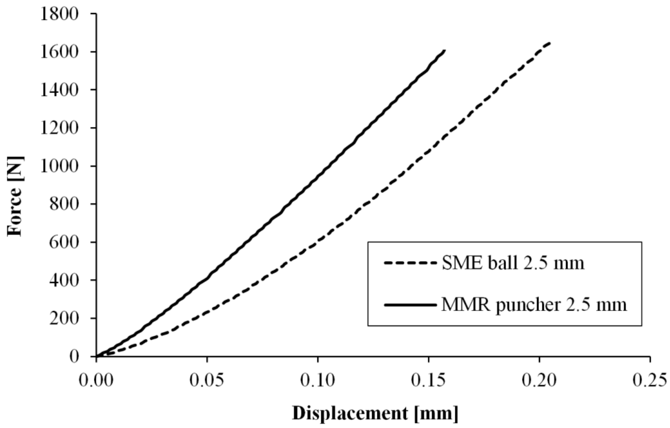

Fig. 5 Differences in stiffness of test rigs used for penetration tests carried out on the testing machine CSS 44 000

Fig. 6 shows the differences in stiffness of testing machines (CSS 44 000, Lab Test 5.10) when the testing rig used in MMR was applied in both laboratories. The comparison of the obtained results have proved that the displacement corresponding to maximum load u_m is affected mainly by the stiffness of the testing machine while the maximum load recorded during SP test is affected by the testing rig probably mainly by the shape of the chamfer edge of the receiving die (see **Fig. 1**).

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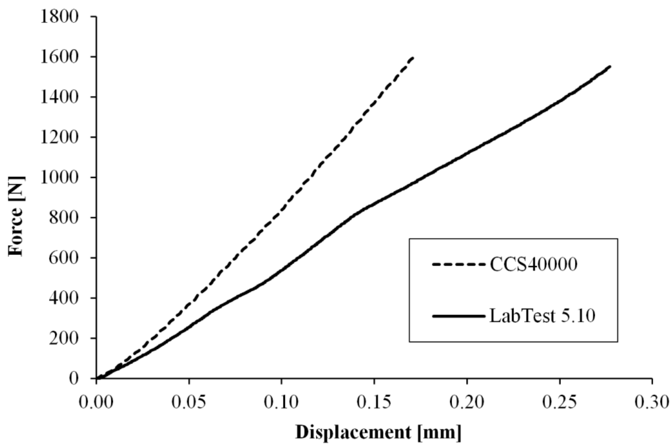

Fig. 6 Differences in stiffness of testing machine (CSS 44 000, Tab Test 5. 10) when used MMR testing rig

5 Conclusions

- Tensile tests results obtained in both laboratories show good agreement.
- Unlike the results of tensile tests, results of the penetration tests at ambient temperature differ significantly.
- The empirical correlations for determination of yield stress and ultimate tensile strength from the results of SP tests obtained in each laboratory are different. The difference can be attributed first of all to the different stiffness of the loading systems.
- The comparison of the results obtained in both laboratories have proved that the displacement corresponding to maximum load u_m is affected mainly by the stiffness of the testing machine while the maximum load recorded during SP test F_m is affected by the testing rig probably mainly by the shape of the chamfer edge of the bore diameter of the receiving die.
- The results obtained suggest that empirical correlations obtained in different laboratories cannot automatically be used for determination of yield stress and tensile strength at room temperature. This fact should be taken into account when revising the document CWA 15627 and during ASTM standards preparation.

References

[1] R.C. Hurst, K. Matocha: *Where are we now with the European Code of Practice for small punch testing?* In: SSTT 2012, Determination of Mechanical Properties by Small Punch and other Miniature Testing Techniques, ed. K. Matocha, R. Hurst, W. Sun, Ostrava 2012, Czech Rep., p. 4-18, ISBN 978-80-260-0079-2

[2] CEN WORKSHOP AGREEMENT "*Small Punch Test method for Metallic Materials*" CWA 15627:2007 D/E/F, December 2007

[3] GBT 29459.1 *Metallic material – small punch test methods for in – service pressure equipment*. Part 1: General requirements

[4] GBT 29459.2 *Metallic material – small punch test methods for in – service pressure equipment*. Part 2: Method of test for tensile properties at room temperature

[5] R. Bruscato: Welding Journal, Vol. 49, 1970, 4, p. 148-156

DOI 10.12776/ams.v20i4.425 p-ISSN 1335-1532
e-ISSN 1338-1156

[6] T. Ishiguo, Y. Murakami, K. Ohnishi, J. Watanabe: *2.25%Cr-1%Mo pressure vessel steels with improved creep rupture strength*. In.: Proceedings of the symposium on Applications of 2.25%Cr-1%Mo steel for thick-wall pressure vessels, ASTM, 1980, p. 129-147
[7] R. Lacalle, J. A. Álvarez, S. Cicero, F. Gutiérrez-Solana: Hutnicke Listy, Vol. 63, 2010, p. 59–68
[8] M. Song, K. Guan, W. Qin, J. A. Szpunar: Nuclear Engineering and Design, Vol. 247, 2012, p. 58-65, DOI: 10.1016/j.nucengdes.2012.03.023
[9] I. I. Cuesta, J. M. Alegre: Engineering Failure Analysis, Vol. 26, 2012, p. 240-246, DOI: 10.1016/j.engfailanal.2012.06.004
[10] J. Purmenský, K. Matocha: *Determination of long term material properties degradation using small specimen testing*. In.: Pressure Vessels and Piping. Vol. IV, Inspection and Life Management. Eds. B. Raj, B. K. Choudhary, A. Kumar, Narosa Publishing House Pvt. Ltd., 2009, New Delhi India, p. 213-220, ISBN 978-81-8487-003-9
[11] J. Bidulská, T. Kvačkaj, R. Bidulský, M. Cabbibo, E. Evangelista: Metalurgija, Vol. 46, 2007, No. 3, p. 157-159
[12] M. Abendroth: *A WEB based approach to identify material properties from SPT experiments*. In: SSTT 2012, ed. K. Matocha, R. Hurst, W. Sun, Ostrava 2012, p. 339-346, ISBN 978-80-260-0079-2
[13] M. Madia, S. Foletti, G. Torsello, A. Cammi: Engineering Failure Analysis, Vol. 34, 2013, p. 189-203, DOI: 10.1016/j.engfailanal.2013.07.028
[14] T. Nakata, S. Komazaki, Y. Kohno, H. Tanigawa: Hutnicke Listy, Vol. 63, 2010, p. 146-150
[15] J. Bidulská, T. Kvačkaj, R. Bidulský, M. Actis Grande: Kovové Materialy, Vol. 46, 2008, No. 6, p. 339-344
[16] R.C. Hurst, K. Matocha: *Experiences with the European Code of Practice for Small Punch Testing for Creep, Tensile and Fracture Behaviour*. In: SSTT 2014, Determination of Mechanical Properties by Small Punch and other Miniature Testing Techniques, eds. K. Matocha, R. Hurst, W. Sun, Castle Seggau, Austria 2014, p. 1- 26, ISBN 978-80-260-6722-1
[17] P. Dymáček, M. Ječmínka: *Applicability of Small Punch Test to Determine the Material Mechanical Properties at Room and High Temperatures*. In: SSTT 2014, Determination of Mechanical Properties by Small Punch and other Miniature Testing Techniques, eds. K. Matocha, R. Hurst, W. Sun, Castle Seggau, Austria 2014, p. 65-74, ISBN 978-80-260-6722-1
[18] K. Matocha: Determination of Actual Tensile and Fracture Characteristics of Critical Components of Industrial Plants under Long Term Operation by SPT. In: American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP, Toronto, Canada, 2012, p. 997-1001, DOI: 10.1115/PVP2012-78553

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