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Measurement of the tensile and yield strength of boiler steels by small punch and tensile test methods

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Abstract. Miniature disk-shaped specimens have been used to evaluate the tensile properties of boiler steels 20, 12Ch1MF, 12Ch11V2MF and 16GNM at room temperature by using the small punch test. Conventional uniaxial tensile tests of standard cylindrical specimens from the same materials have been also performed for comparison. On the basis of comparative analysis a correlation between the maximum punch force and tensile strength has been obtained that allows accurate measurement of the tensile strength with the small punch test. It has been found that the yield strength of the materials could not be determined with sufficient accuracy by means of this test.

Key words: boiler steels, tensile properties, small punch test.

1. INTRODUCTION

The increase of durability and operating reliability of power plant components is of vital importance in thermal engineering. For safe and reliable operation of the equipment it is highly significant to be able to determine the life consumption and to estimate the remaining life of the component or the time till the next mandatory inspection as accurately as possible. It allows to optimize the amount and cost of the inspections and to avoid unscheduled outages and unreasonable replacement of the components, which is expensive.

The components of a power plant suffer material deterioration in terms of strength decrease due to the change in the microstructure of the metal, caused by long-term operation at high temperatures under creep and cyclic fatigue. The influence of the long-term operation on tensile properties of boiler steels has been investigated in [1–8]. It has been shown that long-term exploitation of steel at elevated temperatures besides other changes leads also to the decrease of the tensile strength, measured at room temperature. Tensile strength, measured at the operating temperature decreases considerably more [3]. It has been shown [9] that in some cases the yield strength plays the key role in determining the 3R (run, repair, replacement) decision for a particular component.

In order to get reliable integrity assessment and remaining life estimation, the determination of material properties for in-service components in their current state of damage is very important. One possibility to estimate mechanical properties is the extraction of metal samples from the actual components. Two metal sampling machines, one for sampling from external surfaces of power plant components (Fig. 1) and the other one for sampling from the internal surface of the turbine rotor bore (Fig. 2) have been designed and developed. A detailed review of the metal sampling machines as well as metal sampling experience can be found in [10]. Acceptability of metal sampling from the in-service components has been analysed in [10], where it has been shown that metal sampling by using the mentioned sampling machines does not lead to the initiation of inadmissible stress concentrations. Components could stay in further operation without any loss of safety and the sampled areas did not need repair.

Since the metal samples should be small enough in order to allow continued safe operation of the components, the problem of determining the tensile properties on small test pieces arises. Over the past two decades a number of testing techniques, applicable to miniaturized specimens, have been developed. One of such techniques is small punch (SP) testing, proposed by Manahan et al. [11]. This technique has attracted attention and has been investigated by many researchers [12–19].

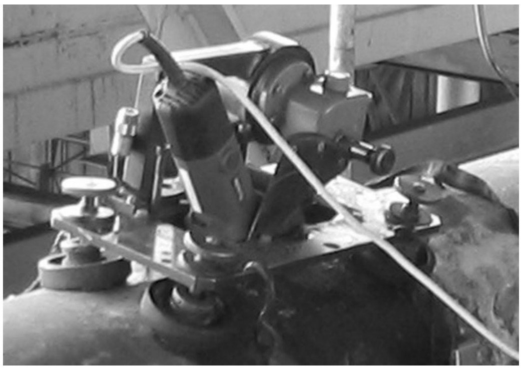

Fig. 1. Device for metal sampling from the external surface of power plant components.

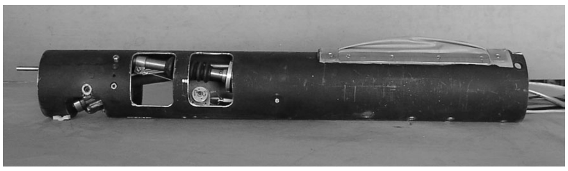

Fig. 2. Device for metal sampling from bores.

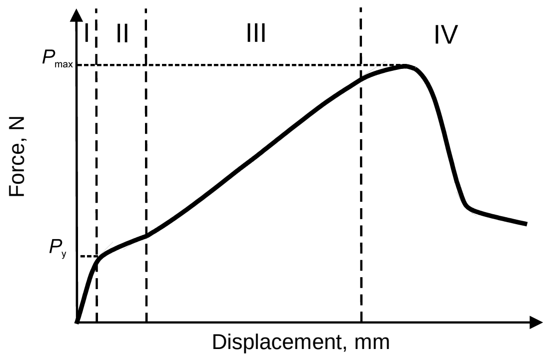

Fig. 3. A typical small punch force–displacement curve.

The SP testing technique is based on the determination of the force–displacement curve for a small disk-shaped specimen under a central force. A typical SP force–displacement curve is presented in Fig. 3. This curve can be divided into four distinct parts: I – elastic bending, II – plastic bending, III – membrane stretching, IV – plastic instability. These four deformation mechanisms have been studied in [20]. On the basis of SP test results, the force F_y that corresponds to the limit of the elastic regime and initialization of plastic deformations and the maximum force F_{max} can be determined. The relationships between these SP test parameters and tensile properties of the material have been obtained and analysed in [12,14,16].

Despite a number of investigations and reported FE studies of SP testing, this method is not yet standardized. Standardization procedures for determining mechanical properties, based on SP testing, are being developed through cooperation of several laboratories (members of EPERC – European Pressure Equipment Research Council) using both experiments and mathematical models. The results of the EPERC round robin provided foundation of the code of practice, which has been recently published as a Workshop Agreement [21].

The aim of the present work is to analyse the possibility to determine the tensile properties of the power plant component materials by means of the SP testing technique with main attention on the yield strength determination.

2. EXPERIMENTAL

In order to analyse the applicability of the SP testing technique for the determination of tensile strength and yield strength of some boiler steels, SP tests and conventional tensile tests were performed at room temperature. In total, 10 metal samples were extracted from power plant components – steam pipes, superheater tubes (20, 12Ch1MF, 12Ch11V2MF) and drum (16GNM). The chemical composition of these steels is presented in Table 1. Afterwards 32 specimens for SP testing and 24 specimens for tensile tests were prepared from these samples.

Table 1. Chemical composition of investigated steels

Steel grade	Content, wt%										
	C	Si	Mn	Cr	Ni	Mo	V	W	Cu	S	P
20	0.17–0.24	0.17–0.37	0.35–0.65	max 0.25	max 0.3				max 0.3	max 0.04	max 0.035
12Ch1MF	0.08–0.15	0.17–0.37	0.4–0.7	0.9–1.2	max 0.3	0.25–0.35	0.15–0.3	max 0.2	max 0.2	max 0.025	max 0.03
16GNM	0.12–0.18	0.17–0.37	0.8–1.1	max 0.3	1.0–1.3	0.4–0.55			0.15–0.25	max 0.04	max 0.035
12Ch11V2MF	0.10–0.17	max 0.5	0.5–0.8	11–13	max 0.6	0.6–0.9	0.15–0.3	1.7–2.2	max 0.3	max 0.025	max 0.03

Steels are designated in accordance with [22].

Manufacturing of standard cylindrical specimens ($d = 3$ mm, $L_0 = 5$ mm) and tensile tests have been carried out in accordance with EN 10002-1:2001. The miniature disk-shaped specimens for SP tests were prepared with dimensions of 8 mm in diameter and 0.5 mm in thickness by punching and machining with subsequent grinding on abrasive paper. The tests were conducted on a testing machine Instron 8516 under a constant displacement rate of 2.5 mm/min. The SP test fixture is shown schematically in Fig. 4. The specimen holder consists of upper and lower dies, supporting the specimen. A thread on the dies (not shown in Fig. 4) is used to apply a clamping force. Thus the disk specimen is clamped between two dies along the perimeter to the distance of 1 mm at the periphery by a force of 7 kN. The specimen is subjected to a central load, which is transmitted from the punch to the specimen by means of a hardened steel ball 4.8 mm in diameter.

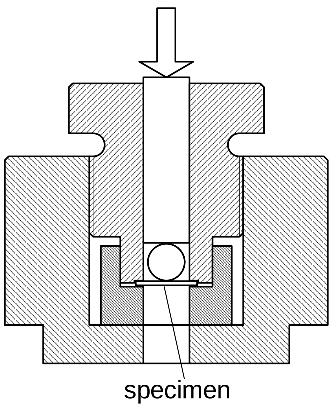

Fig. 4. Small punch testing fixture.

3. RESULTS AND DISCUSSION

The results of the SP and conventional tensile tests are partially presented in Table 2. The high repeatability (0–2%) of the results of tensile strength, determined from tensile tests, are compared with significant lower repeatability (0–5%) of the maximum force measurements from SP tests. The results show that the maximum punch force is linearly related to the tensile strength (Fig. 5). In order to obtain the relationship between SP maximum force (F_{max}) and tensile strength (R_m), a linear least squares regression of experimental data was performed and the following regression equation was obtained (Fig. 5):

$$R_m = 0.184 F_{max} \pm 53, \text{ N/mm}^2, \qquad (1)$$

where ±53 is standard error of the regression equation in N/mm^2.

Table 2. Results of small punch and tensile tests

Steel grade	Small punch test			Tensile test		
	F_{max}, mean, N	Number of specimens	Repeatability*, %	R_m, mean, N/mm^2	Number of specimens	Repeatability*, %
12Ch1MF	3132	4	3	534	3	1
12Ch1MF	2479	2	2	480	2	0
12Ch1MF	2764	3	0	474	2	1
12Ch1MF	2423	3	1	455	2	1
12Ch1MF	2667	4	0	443	3	2
16GNM	2863	3	4	555	2	1
16GNM	2915	3	5	553	2	0
16GNM	3224	3	3	541	2	0
12Ch11V2MF	3846	5	4	823	3	1
20	2807	2	3	468	3	0

* Repeatability is calculated by dividing the standard deviation by the mean value.

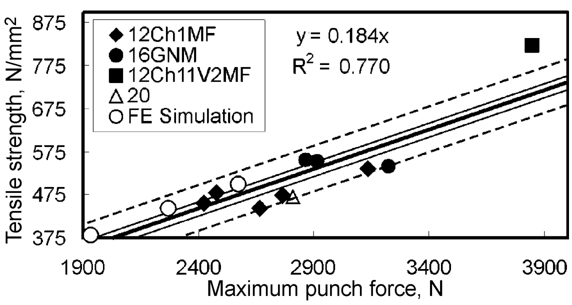

Fig. 5. Relationship between maximum SP force F_{max} and tensile strength R_m of examined steels. Central thick line represents regression equation (1), fine solid lines – standard error of the mean value and dashed lines – standard error of the regression equation. Confidence probability is 68.3%.

Let us consider yield strength determination from SP tests in greater detail. There are two different approaches. The relationship between the yield strength and maximum punch force has been investigated in [14] and shown to follow a linear law for an elastic-perfectly plastic material. However, if both characteristics, the yield strength and the tensile strength, are linearly related to the maximum punch force, then the ratio of yield to tensile strength should be constant. On the basis of experience with common boiler steels it was found [22] that there is no functional relationship between yield strength and tensile strength (Fig. 6a) and the ratio of yield strength to tensile strength varies in a wide range (Fig. 6b). This may be explained by the influence of such factors as creep embrittlement, corrosion embrittlement, etc.

According to another approach for yield strength evaluation on the basis of the SP test proposed in [12,16], the yield strength can be determined as a function of the force, corresponding to the initialization of the plastic deformation. However, it has not appeared possible to determine the transition point from the elastic to the plastic region from the SP force–displacement curves of the investigated steels (Fig. 7). This means that the material yield strength could not be determined with sufficient accuracy using SP tests, neither on the basis of

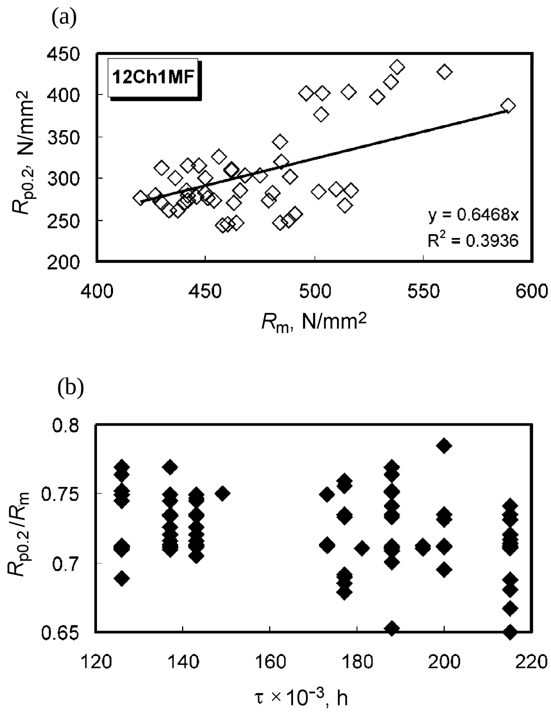

Fig. 6. (a) relationship between the offset yield strength $R_{p0.2}$ and tensile strength R_m of the steel 12Ch1MF; (b) dependence of the ratio of the offset yield strength to the tensile strength ($R_{p0.2}/R_m$) of the steel 12Ch1MF on the operation time τ.

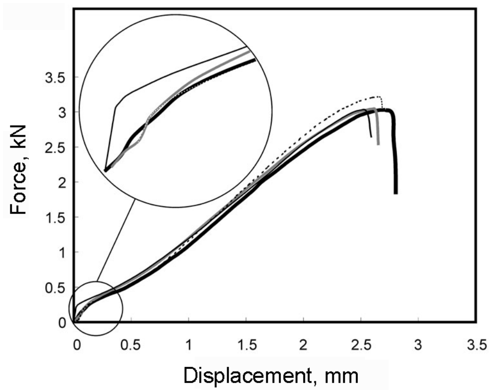

Fig. 7. The force–displacement curve at room temperature, obtained from SP tests of the steel 12Ch1MF.

maximum punch force nor on the basis of the force, corresponding to the initiation of plastic deformation.

4. CONCLUSIONS

Small punch tests of miniature disk-shaped specimens and conventional tensile tests of standard cylindrical specimens have been performed at room temperature with some commonly used boiler steels. The comparison of the results has shown that tensile strength of the metal can be reliably obtained as a linear function of the maximum punch force, determined in the small punch test. On the basis of conducted experiments it has been found that yield strength of the materials could not be determined with sufficient accuracy by means of small punch tests, neither on the basis of maximum punch force nor on the basis of the force, corresponding to the initiation of the plastic deformation.

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Aurukatlateraste tõmbetugevuse ja voolepiiri mõõtmine kuuliga surumise ning tõmbekatse meetodil

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Aurukatlateraste 20, 12Ch1MF, 12Ch11V2MF ja 16GNM tõmbetugevuse ning voolepiiri määramiseks kasutati miniatuursete kettakujuliste teimikute (läbimõõduga 8 mm ja paksusega 0,5 mm) kuuliga surumist (*small punch tests*). Teimikud valmistati katsekehadest, mis olid välja lõigatud soojusjõuseadmete elementide pinnalt. Selle katsemeetodi kasutusvõimaluse analüüsiks viidi paralleelselt läbi võrdlustõmbekatsed, kus kasutati standardseid silindrilisi teimikuid, mis olid valmistatud samadest katsekehadest. Katsetulemuste võrdlus näitas, et tõmbetugevust saab kuuliga surumisega määrata piisava täpsusega, kuid voolepiiri määramise täpsus on ebarahuldav.