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Assessment of Damage of Metallic Elements in Oil and Gas Facilities using Small Punch Test

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Abstract

The paper describes possibility of mechanical property investigations using small-sized specimens (Small Punch Test or SPT) to assess degradation of metallic materials of oil and gas equipment and pipelines. SPT is proposed as non-destructive method since it does not affect operating capacity of the evaluated objects. According to the results of the test, diagram "stress – displacement" is constructed that contains characteristic points: the first point differentiates the elastic and plastic strain zones; the second point differentiates the moment of destruction of the specimen. Assessment of damage of the specimens is carried out by comparing the position of these characteristic points on the diagram for original intact specimens and specimens subjected to prior plastic strain.

Keywords: miniature specimen, Small Punch Test, mechanical behavior, structural steel, charting.

Currently, there is a need for real-time monitoring of metal health of elements in oil equipment and production facilities. This leads to extensive development of innovative methods. One of the most promising among them is the indentation test or Small Punch Test (SPT), which is based on the use of miniature specimens. It can be used to estimate physical and mechanical property changes and level of material damage. The main advantages of this method are:

- it can be considered as a non-destructive test method, since the production of specimens from the metal of operating equipment does not reduce its efficiency because of the small size (thickness is less than 1 mm);

- indentation tests of small-sized specimens do not require much time and material resources;

- the opportunity to study elements such as the heat-affected zone of a weld, details of small size or complex shape, as well as elements from material that is too fragile for uniaxial tension test, or destroyed details, which cannot be used for carving full-sized specimens in accordance with standards, etc.

In comparison with nondestructive methods such as ultrasonic, magnetic and radiographic testing, SPT is a method of direct measurements, which allows to obtain mechanical properties of the material, while other methods are based on the assessment of indirect indicators.

Principle of the SPT method consists in punching the indenter with a hemispherical or cylindrical tip into a small-sized specimen until its fracture (Fig. 1). During the test, loading rate (N) and displacement of the indenter (mm) are controlled, after which the graph is built, as shown in Fig. 2.

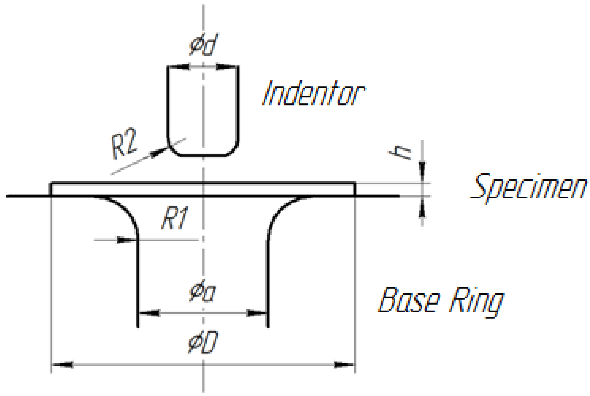

Figure 1: Scheme of test

The main problems, arising when assessing the results of the test, were associated with obtaining correlations between SPT results and standard tests, e.g., uniaxial tension test [1-12].

A wide range of correlation of SPT results with the determination of fracture toughness has been proposed in high-tensile zone [1-7] and a few in fragile zone [3]. Correlations between SPT and uniaxial tensile tests are proposed, for example, in [8-12].

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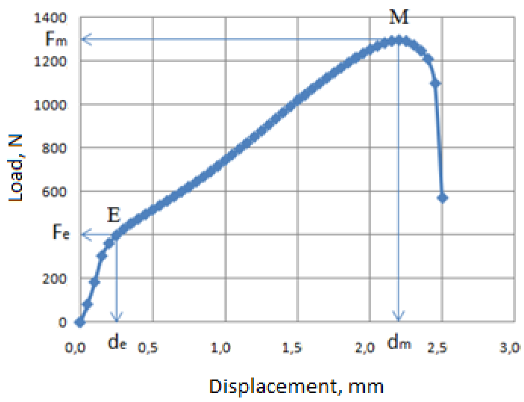


Figure 2: «Force – displacement» graph

The drawback of SPT is a method of load application, which is not uniaxial, as in the case of standard one-dimensional tensile tests, and this causes the absence of direct correlation between tensile tests and SPT. Therefore, the correlation of SPT data with data obtained during tensile tests is usually done on the basis of empirically established correlations.

Low-carbon steel (St3 according to Russian grading system) was selected as the test material because of its high incidence in the manufacture of elements of oil and gas equipment, piping and metal structures of production facilities.

At the first stage, uniaxial tensile tests of the selected steel grades were carried out in accordance with GOST 1497-84 (Russian National State Standard). Specimens with a diameter of 6 mm and a length of 65 mm were used (3 pcs). Empirical tensile stress-deformation diagram is shown in Fig. 3 and estimated characteristics are shown in table 1.

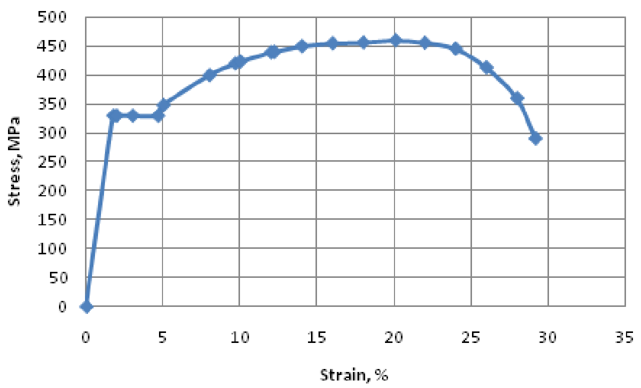


Figure 3: Average chart of tensile of steel St3

Table 1:. Characteristics of steel St3

E, GPa	$\sigma_{0,2}$, MPa	σ_{UTS}, MPa	δ, %
34,2	332,7	456,7	29,2

Small Punch Test was performed on a Zwick/Roell Z100 materials testing machine. The geometric features are listed in table 2. A total number of 27 specimens, 3 of each size, were tested.

Table 2. Geometric features

Feature name	Designation, unit	Value
1	2	3
Specimen: diameter	D, mm	5,0; 10,0; 20,0
thickness	h, mm	0,5; 1,0; 1,5
Indentor: diameter	d, mm	2,0
radius	R_2, mm	0,1
Base ring: diameter	a, mm	4,5; 9,0; 18,0
radius	R_1, mm	0,5

The sequence of actions in conducting the test consists of installation of lower die or base ring in the machine, fixation of the indenter using rotary fastener, installation of the test specimen on the lower die / base ring, punching it under static load at a speed of 0.2 mm/min inside the die / ring until the fracture of the specimen.

Processed graphs, obtained in the tests, are represented in Fig. 4 – 6. Two characteristic points can be distinguished: point E, corresponding to the transition from elasticity to the spread of plastic zone through the thickness of the specimen, and point M, corresponding to the maximum load recorded during the test (Fig. 2). Change in the values of projections of the points Fe, de, Fm, dm, depending on the dimensions of the specimens are shown in table 3.

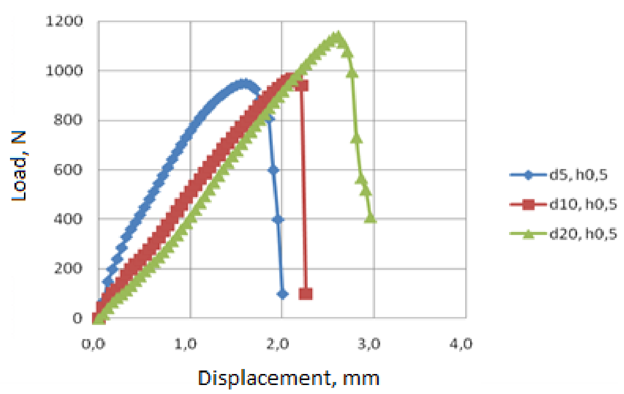


Figure 4: Test results for specimens with thickness 0,5 mm

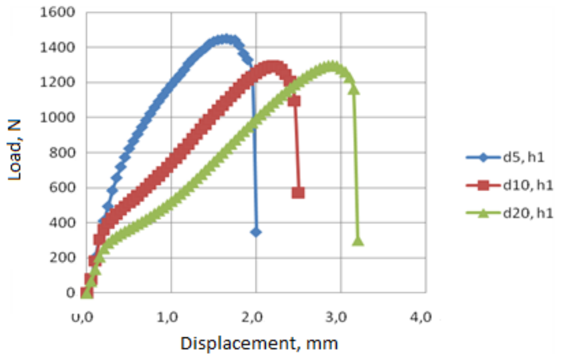


Figure 5: Test results for specimens with thickness 1 mm

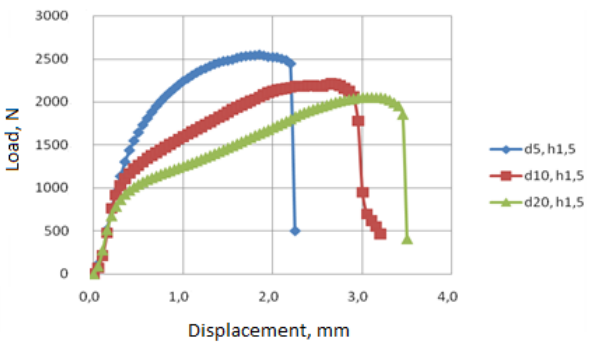


Figure 6: Test results for specimens with thickness 1,5 mm

Table 3. Values of the monitored experimental parameters

Dimensions of specimens		Coordinates of the "E" point		Coordinates of the "M" point	
d, mm	h, mm	F_e, N	d_e, mm	F_m, N	d_m, mm
1	2	3	4	5	6
5,0	0,5	200	0,15	950	1,60
5,0	1,0	585	0,30	1450	1,65
5,0	1,5	1545	0,45	2543	1,85
10,0	0,5	102	0,15	967	2,12
10,0	1,0	362	0,20	1296	2,20
10,0	1,5	917	0,25	2214	2,65
20,0	0,5	84	0,20	1140	2,60
20,0	1,0	255	0,20	1300	2,90
20,0	1,5	785	0,25	2050	3,10

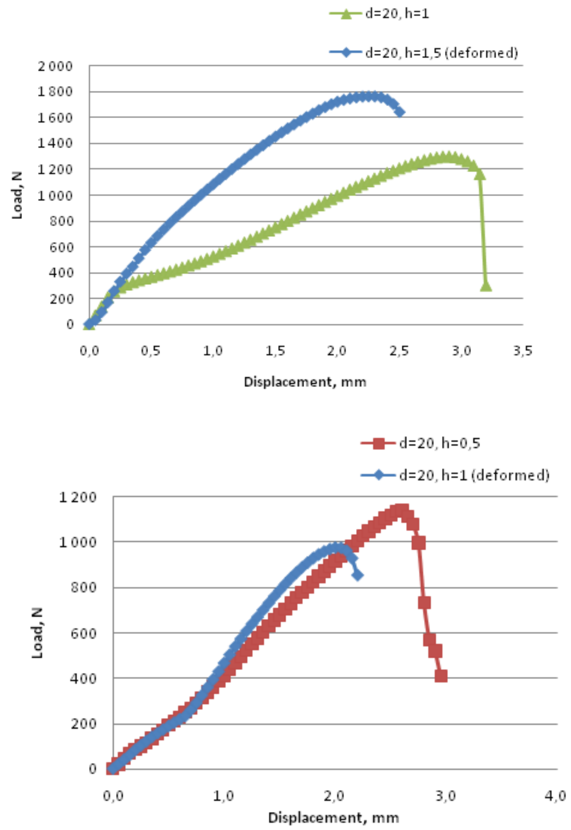
According to the obtained results, it can be concluded that the increase in diameter leads to increase in the maximum load during the test (F_m), while the increase in thickness leads to increase of the indenter displacement corresponding to maximum load (d_m).

For comparative assessment of changes in physical and mechanical properties by the SPT method, pre-deformation of specimens from steel St3 was carried out with treadle hammer. Subsequently, these specimens were tested as described above. Diameters and thicknesses of specimens, which were obtained after carrying out plastic deformation with the hammer, are shown in table 4.

Table 4. Dimensions of specimens after plastic deformation

№	D_1	D_2	h_1	h_2	№	D_1	D_2	h_1	h_2
1	20	23,8	1,5	1,4	10	20	22,6	1	0,9
2	20	24,6	1,5	1,3	11	20	23,7	1	0,8
3	20	25,5	1,5	1,1	12	20	24,3	1	0,8
4	10	14,1	1,5	1	13	10	14,3	1	0,7
5	10	14,8	1,5	0,9	14	10	14,6	1	0,7
6	10	15,6	1,5	0,8	15	10	15	1	0,8
7	5	7,1	1,5	0,9	16	5	7,2	1	0,6
8	5	7,5	1,5	0,8	17	5	7,3	1	0,6
9	5	7,7	1,5	0,7	18	5	8,4	1	0,5

The graphs, obtained during testing of specimens subjected to prior deformation, are shown in Fig. 7 – 9.

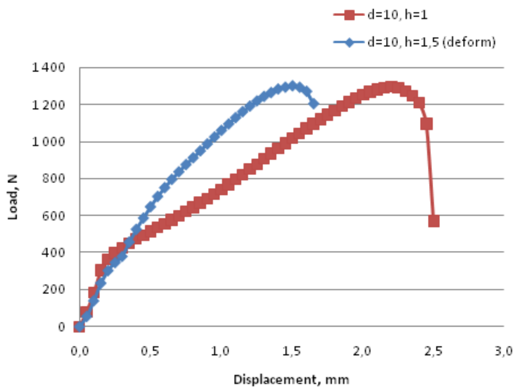


a)

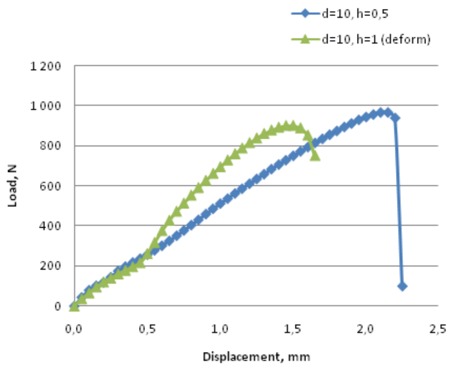
b)

Figure 7: Test results for deformed specimens:

a) 20,0x1,5 mm; b) 20,0x1,0 mm

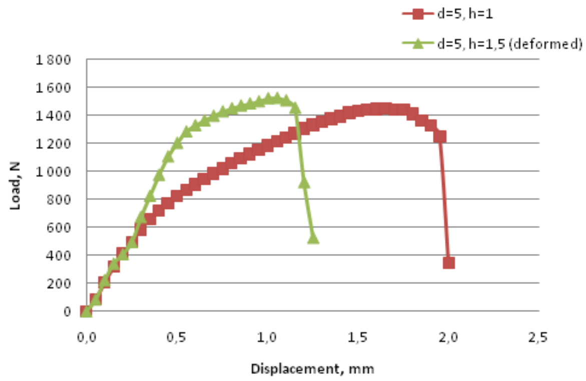


a)

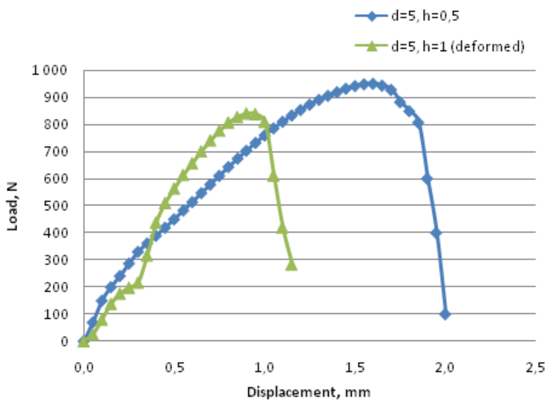


b)

Figure 8: Test results for deformed specimens: a) 10,0x1,5 mm; b) 10,0x1,0 mm



a)



b)

Figure 9: Test results for deformed specimens: a) 5,0x1,5 mm; b) 5,0x1,0 mm

Graphs show two curves – the characteristics of the initial condition and deformed condition. The curves clearly demonstrate that the specimens subjected to prior deformation significantly differ in their characteristics from the specimens in initial condition, which is also shown in table 5.

In all cases decrease in d_m for 25...70% was recorded. Furthermore, in most cases increases in F_e and d_e in the range from 8 to 70% were recorded.

Table 5. Change of controlled parameters for specimens in initial and deformed conditions

Initial condition		Deformed condition		Value changes, %			
1	2	3	4	5	6	7	8
d, mm	h, mm	d, mm	h, mm	ΔF_e	Δd_e	ΔF_m	Δd_m
5,0	0,5	5,0	1,0	7,79	50,00	-12,76	-77,78
5,0	1,0	5,0	1,5	13,30	0,00	4,96	-57,14
10,0	0,5	10,0	1,0	61,03	70,00	-7,50	-41,33
10,0	1,0	10,0	1,5	-19,44	0,00	0,31	-46,67
20,0	0,5	20,0	1,0	71,09	73,33	-16,59	-30,00
20,0	1,0	20,0	1,5	62,67	63,64	26,29	-26,09

Thus, the test results of the proposed method allow to obtain information about the change in the stress-strain state of metal in the oil equipment and operating facilities.

Values of the parameters of the characteristic points E and M, obtained in the result of the SPT, demonstrate operability of considered elements of metal structures. For an invariable position of the points in the zone of elastic deformation, the metal will have a reserve of operability, and in case of change in the points' position, it is possible to ascertain the onset of inoperable condition caused by plastic strain of the metal. When evaluating the stress-strain state for most elements of equipment and structures, this is limit and unacceptable state.

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