CONTROL OF PHYSICAL AND MECHANICAL CHARACTERISTICS OF STEEL BY SMALL PUNCH TEST METHOD

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Abstract. Analysis of applicability of methods using microspecimens indentation tests to determine the physico-mechanical characteristics of steels, as well as the damage state of the material by the example of steel 10 and steel 20, was conducted. The dependency of the load value, to which the steel was subjected, on specific characteristics obtained by testing microspecimens was received.

1. Introduction

Currently, the use of small-sized specimens in oil and gas industry as a method for determining the damage of in-service pipelines and equipment is becoming more and more promising [1]. One of the most commonly used techniques is the bending test of small disk-shaped specimens (Small Punch Test – SPT). Although this technique has been used for more than 30 years, there is still no generally accepted procedure for determining the basic physical and mechanical properties by SPT data. This method has been applied not only in the oil and gas industry, but also in various other industries, including mining, nuclear and diagnostics of composite materials and biomaterials [2, 3].

SPT involves pressing punch with hemispherical tip into a specimen until the specimen is destroyed. In this case, the load value (N) and the displacement of the indenter (mm) are fixed. Taking into account the local changes in physical and mechanical properties, the methodology proposed allows an assessment of pipeline section/facility residual life [4].

2. Results and discussion

For evaluation of damage of test material (pipeline steel 10 and steel 20 as per GOST 1050-88), tests were conducted on specimens with a 10 mm diameter and 1 mm thickness for two initial conditions:

− undamaged;
− previously exposed to external loads with accumulated internal stresses and strains.

First, standard specimens as per GOST 1497-84 «Methods of tension test» (fig. 1) were produced to carry out the experimental part of research.
Some of the standard specimens were subject to tension load up to different values using test machine Zwick/Roell Z100. For steel 20, the value of pre-load was as follows (fig. 2):

1) less than yield stress value (17 kN);
2) approximately the same as the yield stress value (20 kN);
3) above the yield stress value (25 kN);
4) almost the same as the ultimate tensile strength value (30 kN).

After removal of the tensile load, internal stresses and plastic irreversible deformations remain in the steel, the nature of which is similar to the damage accumulated during the operation of steel of oil and gas pipelines and facilities. Furthermore, standard specimens are cut into small sized specimens (66 - for steel grade 10, 55 - for steel grade 20).

Small Punch Test was carried out using test machine Zwick/Roell Z100 with special tooling (punch, upper/lower dies). Test configuration is shown in fig. 3. A working tool, by which the small sized specimen is indented, has a hemispherical tip made of chisel steel U8 (as per GOST 1435-99) exposed to hardening and high-temperature tempering. Other tooling, i.e. upper and lower dies with threaded connection, made from steel 45 (as per GOST 1050-88), is designed for holding the specimen fixed and
directing the punch [5, 6]. According to the obtained data, the «force – displacement» diagram is plotted, which determines the characteristic points: \( F_e \) (elastic-plastic transition force) and \( F_m \) (the maximum force), and corresponding displacements \( d_e \) and \( d_m \) [7, 8].

![Diagram of SPT method](image)

**Figure 3.** SPT method: a – geometrical parameters of small sized specimen, b – test configuration

While \( F_m \) and \( d_m \) can be easily obtained from the diagram, \( F_e \) and \( d_e \) coordinates can be obtained only using bi-linear fit as recommended by CWA 15627:2007 [9] since plasticity occurs consistently in different areas of small sized specimen. Accordingly, “two tangents method” was used in this study. In this case, \( F_e \) is identified as projection of the intersection point of two linear functions on the force-displacement curve (fig. 4) [1].

![Force-displacement curve](image)

**Figure 4.** Determination of \( F_e \) (by means of bilinear fitting) and \( F_m \)

To establish numerical values of yield stress and ultimate tensile strength of material from SPT data, empirical correlations [1, 6, 10] should be used, since the force in this method is not uniaxial.
Fig. 5 and tables 1, 2 show averaged «Force-displacement» curves obtained from SPT data and corresponding characteristic values.

![Figure 5](image_url)

Table 1. Characteristic values obtained from SPT (steel 10)

| № on diagram (fig. 5a) | Pre-load, kN | F_{m}, N | d_{m}, mm | F_{c}, N | d_{c}, mm |
|------------------------|--------------|----------|------------|----------|------------|
| 1                      | 25           | 3241     | 2,11       | 755      | 0,28       |
| 2                      | 23           | 3201,5   | 2,09       | 735      | 0,26       |
| 3                      | 20           | 3035     | 2,05       | 693      | 0,24       |
| 4                      | 17           | 2778,5   | 2,02       | 655      | 0,21       |
| 5                      | 13           | 2546     | 1,97       | 505      | 0,17       |
| 6                      | 0            | 2424     | 1,94       | 480      | 0,14       |

Table 2. Characteristic values obtained from SPT (steel 20)

| № on diagram (fig. 5b) | Pre-load, kN | F_{m}, N | d_{m}, mm | F_{c}, N | d_{c}, mm |
|------------------------|--------------|----------|------------|----------|------------|
| 1                      | 30           | 4032     | 2,01       | 1280     | 0,35       |
| 2                      | 25           | 3769     | 1,97       | 1130     | 0,33       |
| 3                      | 20           | 3358     | 1,92       | 970      | 0,29       |
| 4                      | 17           | 3104     | 1,9        | 802      | 0,26       |
| 5                      | 0            | 3025     | 1,89       | 774      | 0,25       |

In reviewing the obtained data, it appears that by means of SPT it is possible to record the change in mechanical properties on the small sized specimens exposed to pre-load in comparison to undamaged steel specimens.

With the increase of pre-load value, gradual increase in the values of SPT characteristic point can be observed. The rational for this is the process of accumulation of internal stresses and irreversible deformations in pipeline steels, and consequently, hardening and embrittlement.

According to SPT data (tables 1 and 2), linear relationships (1) – (2) between pre-load value and the maximum force F_{m} recorded during SPT were obtained by an ordinary least-squares technique (fig. 6):
for steel 10 – \( N = 0.015 \times Fm - 23.86 \),
for steel 20 – \( N = 0.014 \times Fm - 25.90 \). (1)

Similarly, linear relationships (3) – (4) between pre-load and elastic-plastic transition force \( F_e \), which can be considered as an analogue to yield stress from the standard tension test, were obtained (fig. 7):

for steel 10 – \( N = 0.042 \times Fm - 9.03 \),
for steel 20 – \( N = 0.028 \times Fm - 5.77 \). (3) (4)

Thus, using the data obtained by SPT (\( F_e \) and \( F_m \) values) and derived dependencies (1) – (4), it is possible to determine the value of the pre-load, to which the steel grade 10/20 was subjected while in service. The obtained value makes it possible to predict the technical condition and health of pipeline/facility for a certain period in the future.

3. Conclusion
Based on the results of the experimental part of metal testing (steel 10 and steel 20), the following conclusions were made:
- the example of pipeline steel 10 and steel 20 showed that small sized specimens and SPT method can be used to determine the material condition via values of characteristic points, in particular maximum force and elastic-plastic transition force;
- according to the received experimental data, having accumulated internal stresses and deformations, pipeline steels have tendency to gradual hardening and embrittlement;
- linear dependencies (1) – (4) with high accuracy describe the relationship between the state of steel and the results obtained by SPT method.

References
[1] Bruchhausen M, Holmström S, Simonovski I, Austin T, Lapetite J-M, Ripplinger SF. de Haan 2016 Recent developments in small punch testing: Tensile properties and DBTT Theoretical and Applied Fracture Mechanics 86 2-10
[2] Serebryannikov A A, Serebryannikov D A, Hakimov Z R 2017 Justification of indirect methods of bending stresses polyethylene pipes evaluation IOP Conference Series: Earth and Environmental Science 87
[3] Maksarov V V, Olt J J 2014 The use of anisotropy of metals to influence the dynamic properties of mechanical systems (Saint Petersburg Polytechnic University)
[4] Zvonarev I, Ivanov S, Fokin A, Shibanov D 2014 Residual life estimation for coarse-pitch gear wheel of mining machinery on the basis of local changes in surface hardness Journal of Mining Institute 209 31-36
[5] Siegl J, Stephan J, Kopriva R, Eliashova I 2015 Assessment of mechanical properties of component materials in nuclear power plants using modern methods and their comparison with standard mechanical testing Proceedings of 17-th International scientific-technical conference of young specialists on nuclear power units (Podolsk: OKB Gidropress JSC) 10-17
[6] Lacalle R, Alberto J, Álvarez, Cicero Gutiérrez-Solan 2010 From Archaeology to Precious Metals: Four Applications of Small Punch Test Hutnické listy LXIII 123-127
[7] Džugan J, Konopík P 2010 Evaluation of fracture toughness properties for low carbon steel in the brittle state by small punch test technique Hutnické listy LXIII 119-122
[8] Karel M 2007 Nondestructive evaluation of mechanical characteristics of in-service components, materials by Small Punch Test NDT for Safety 145-152
[9] Small Punch Test Method for Metallic Materials, Part B: A code of practice for small punch testing for tensile and fracture behaviour (CEN Workshop Agreement, CWA)
[10] Ottosson J B 2010 Development and Evaluation of a Small Punch Testing Device (Linköpings universitet)