Pipeline mechanical properties determination using non-destructive method with consideration of microstructural changes

M.O. Karpash*, Ye.R. Dotsenko, O.M. Karpash

Ivano-Frankivsk National Technical University of Oil and Gas;
15, Karpatska Str., Ivano-Frankivsk, 76019, Ukraine

Received: 11.03.2014   Accepted: 12.11.2014

Abstract

Existing pipeline networks used for transportation of oil and gas are being exposed for operation for decades resulting in serious material degradation process occurs in such cases. In this research results of experimental investigation aimed at determination of the electrical resistivity of structural steels used in gas transmission pipelines with the help of the developed experimental unit that implements the four-point method was studied. Multi-parameter approach was utilized in the study while neural networks were used for non-linear approximation of yield strength of pipelines as a function of hardness and electrical resistivity. Samples with special heat-treatment for microstructure distinguishing as well as a number of samples taken from the long-term used pipelines were selected. Destructive tensile testing was performed for all samples under investigation and results were used as references in the study. It was shown that the four-point method can be used to overall metal structures, since the measured value of electrical resistivity does not affect the whole width of the object of control, but only so-called conditional effective width. Under the conditional effective width of the sample should be understood that part of the sample, in which the density of direct current passing through the object, is the largest and which actually affects the measured value of electrical resistivity. Combined measurement of the hardness together with electrical resistivity after neural network processing showed to achieve 26 MPa accuracy for yield strength determination at real-life pipelines.

Keywords: *electric resistivity, hardness, neural networks, pipelines, yield strength.*

Introduction

The problem of ensuring oil and gas transmission pipelines reliable and safe operation is becoming of high priority in the last decades because their wear-and-tear essentially exceeds the rates of technical re-equipment. During the operation metal construction materials face damages, nature of which depends on the load type and operation conditions (cyclic loading, extreme temperatures, corrosive environment etc). Combined effects of these factors in operational conditions result in changes of microstructure and mechanical properties of pipeline materials.

Crucial need for such a problem solutions can be confirmed by its correspondence to the main provisions of the Ukrainian State Scientific Technical Program "Resource". According to the Program Concept for 2010–2012 one of the priority research areas was “development of effective non-destructive methods and instruments for evaluation of construction stress states and physical and mechanical properties in operating conditions”.

In addition, a wide range of steel materials, used for critical components manufacturing and variety of technological processes, which influence physical and mechanical properties formation requires strict quality control of products. Additionally significant number of equipment such as pipelines with lost operational documentation and operating under variable conditions are still used in production facilities of many Ukrainian enterprises. This aspect is also essential for monitoring actual mechanical characteristics of materials.

Industrial experience [1] shows that for a long-term operation for several decades mechanical properties of metals vary in comparison with their nominal values. In particular:

durability (hardness, yield strength, tensile strength) increased mainly by 10–15%;

visco-plastic parameters (relative elongation, relative narrowing) – reduced by 5–7%;

indicators of resistance to brittle fracture (impact strength and fracture toughness) – reduced to 15–20%.

In our research we have focused on the most important mechanical property of oil and gas transmission pipeline materials with expired life as the yield strength.

Significant role in determination of entire complex of mechanical properties and quality of manufactured products have non-destructive physical methods of testing, development of which attracts attention from researchers [2]. However, existing non-destructive evaluation of physical and mechanical properties is based mainly on certain parameters such as hardness and coercivity. They are found to be not quite informative and have a number of shortcomings and

* Corresponding author: mkarpash@nung.edu.ua

assumptions concerning its theory and practical implementation [3].

Problem statement

Main idea of research stands on the fact that steel mechanical properties are predetermined by microstructure of the steel, which from the another side can be evaluated by resistivity measurements. In fact changes of mechanical properties are usually caused by structural changes in metal, thus the strength properties are being changed together with plasticity reduction.

The aim of this work is development of method and instrument for evaluation of steel mechanical properties and establishment of the dependence of mechanical properties (yield strength) with informative parameters (resistivity and hardness). In this paper results of investigation aimed on relation establishment between electrical resistivity and yield strength on real-life pipeline steels are presented.

Theoretic investigation

Multi-parameter complex approach

Nowadays a significant attention is given to development of integrated approaches to pipeline mechanical properties evaluation involving simultaneous consideration of several informative parameters. Special interest is given to methods that take into account informative parameters related with different physical phenomena (magnetic, electrical, thermal etc.) [4].

Elaboration of new methods for multi-parameter evaluation requires solution of two major problems:

selection of optimal set of control parameters;

development (or selection among available) of the instruments.

Usually relationships between the mechanical, physical and structural properties of materials are being established based on statistical methods. These methods allow to process large amount of information, obtained during long-term investigations as with taken from material databases.

In practice of non-destructive testing electric resistivity measurements are used for metal sorting, alloys composition identification and crack detection by local changes in conductivity of the material. Also by change in resistivity we can point out microstructural changes in metals [5], especially used in oil and gas pipelines. Recent research [6] indicates the possibility of determining impact strength of steels on the measured values of resistivity.

Electrical resistivity varies with the change of steel microstructure and thus influence on mechanical properties of steels as proved by [5]. Considering structural dependence with steel physical and mechanical properties, it is expedient to use this fact for selection of structurally sensitive informative parameters. Detailed discussion to this issue is given in [7].

For accurate determination of the resistivity the most widespread are eddy current and electric-contact methods [8]. Application of eddy current method applies only to non-magnetic metals, because the output signal of eddy current transducer is affected by magnetic permeability of magnetic material. Therefore the most appropriate is usage of direct current electric-contact methods, which, moreover, allow receiving information on the resistivity of the metal volume, which can't be achieved by eddy current method due to the presence of skin-effect.

Electric-contact methods include two-, four-point probe methods and Van der Pauw method [9]. Use of two-point probe method on real steel objects for in-situ measurements is quite problematic. The method of Van der Pauw allows to measure electrical resistivity of samples with arbitrary geometrical form, but it is difficult to realize technically, as it requires individual placement of probes depending on the sample form. Therefore, the most universal method of measuring materials resistivity should be a classic four-point probe method.

For accurate determination of the resistivity mathematical modelling of control resistivity of flat specimens of rectangular shape by four-probe method was carried out, so it helped to establish analytical expressions that describe the influence of metal construction finite size on measurement results [10].

Theoretical investigation of the method

At first stage authors showed that yield strength of steels can be determined by electric resistivity within the structural groups [11] using correlation and statistical analysis. Such dependence was found to be non-linear and positive.

In order to check the above mentioned theoretical idea data for 142 carbon steel grades which were taken from [www.matweb.com] and divided into following structural groups:

austenitic steels (88 grades);

ferritic steels (12 grades);

duplex steels (26 grades);

martensitic steels (16 grades).

For the parameter complex selection the following properties were taken into consideration:

yield strength (145–1,800 MPa);

hardness (140–332 HB);

electric resistivity (500–1,450 nOhm·m).

According to the previously developed approach neural networks were used for establishment of structural dependence with hardness and electric resistivity considering its non-linear nature. Neural network require training procedure and testing, thus all steels grades were divided into three different training and testing sets of data:

1st set includes austenitic and duplex steels (training set – 90 grades, testing – 5 grades)

2nd set contains ferritic and martensitic steels (training set – 37 grades, testing – 3 grades)

3rd set includes all steel grades of all structures (training – 127, testing – 6).

Neural network of the defined architecture was trained for approximation of yield strength as a function of two informative parameters – electric resistivity and hardness.

Table 1 – Neural network testing results

Steel		1	2	3	4	5	6	7	8	Testing error	
										MPa	%
Data set	Real yield strength values	275	310	485	280	450	275	350	560	–	–
1st	Neural network outputs	271	313	492	283	430	–	–	–	7.4	3.52
2nd	Neural network outputs	–	–	–	–	–	273	384	562	12.6	4.42
3rd	Neural network outputs	276	316	483	273	379	328	345	478	28.3	9.92

.

According to the adopted practice neural network testing was performed on the data which were not used for training (e.g. unknown for networks). Pre-processing of the input and output data was performed by normalization. Levenberg–Marquardt training algorithm was used for all networks as being proved to fit small networks with good convergence [12].

Neural network architecture selection, data pre-processing and training algorithm has been done based on investigator prior experience [4] and strongly depends on complexity and nature of the problem as well on availability of statistical data. As basic architecture $20 \times 10 \times 1$ was selected what means that first hidden layer is composed of 20 neurons, second layer with 10 neurons and 1 output neuron. Testing results for three data sets are given in Table 1.

Thus determination of the steel mechanical properties within groups with the same and similar structure enable to increase accuracy of determination in 2–3 times which strongly corresponds with known structural state and their mechanical properties.

Experiments and experimental setup

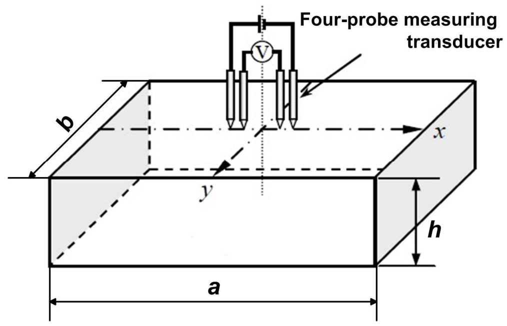
Experimental procedure

Four-point probe method principle of measuring the resistivity is as follows [8]. On the surface of control object along a straight line measurement transducer is placed, which contains four metal electrodes-probes with a small contact area (Fig. 1, a). Two external probes pass an electric current generated by DC source. Two internal probes measure the voltage drop (Fig. 1, b). According to the measured values of differential potential and current it is possible to determine the resistivity of the sample material.

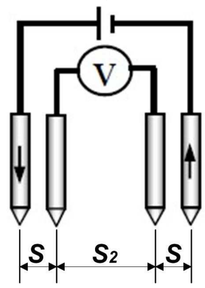
In the case of a four-probe measuring transducer placing in the centre of the rectangular sample, in which the probes are placed along the centre line parallel to the longest side of the sample (Fig. 1, a) electrical resistivity is calculated by formula [9]:

$$\rho = \frac{U}{I} 2\pi S\ f(m, a/S, b/S, h/S), \quad (1)$$

where U is voltage drop, I is current intensity, $f(m,a/S,b/S,h/S)$ is geometric correction function, which depends on real finite size (as length a, width b and thickness h) of rectangular sample and the ratio of the linear dimensions of probes $m = S_2/S$, S is distance between the current and corresponding potential probes, S_2 is distance between potential probes (Fig. 1, b).



a)



b)

Figure 1 – Four-probe method for resistivity measurements

As a result of mathematical modelling by applying the method of mirror reflections, formula for calculating geometric correction function was obtained as following:

$$f\left(m, \frac{a}{S}, \frac{b}{S}, \frac{h}{S}\right) = \left(\frac{-2m}{m+1} + \sum_{k=0}^{\infty}\sum_{n=0}^{\infty}\sum_{g=0}^{\infty} \left[(-1)^k \left\{ 2\left[n^2 (b/S)^2 + (k(a/S) \pm 1)^2 + 4g^2 (h/S)^2 \right]^{-1/2} - 2\left[n^2 (b/S)^2 + (k(a/S) \pm [m+1])^2 + 4g^2 (h/S)^2 \right]^{-1/2} \right\} \right] \right)^{-1}, \quad (2)$$

where k, n, g are numbers of levels of perceived power sources that are entered for the spatial construction of mirror reflections in three-dimensional coordinate system in order to carry on all sides of the sample of homogeneous Neumann conditions (normal component of current density on all sides is equal to 0).

In order to avoid separate measurement of current intensity and voltage drop, it is advisable to use micro-ohmmeter, because the principle of electrical resistance measurement is based on four-probe method. In addition, theoretical studies have shown that for determination of small values of steel resistivity with an error of $\pm 10^{-8}\,\Omega \cdot m$, a device for resistance measuring should represent by micro-ohmmeter.

Then formula (1) can be presented than as:

$$\rho = 2\pi RSf(m, a/S, b/S, h/S), \qquad (3)$$

where R is micro-ohmmeter readings.

Experimental Setup

The main components of the developed information-measuring system are the unit for measurement of the resistivity by four-probe method, which consists of contact and measurement units. Requirements for a contact block are following:

a) Optimal size of probes relative position for high method sensitivity

b) One-side access to the surface of the control object (conditions of pipelines under operation)

c) High strength probes material.

The requirements for the measurement unit are high input impedance of voltage meter to avoid the influence of contact resistance on the measurement results and possibility of measuring low values of active electrical resistance.

As the measurement unit certified micro-ohmmeter BSZ-010-2 (produced by Samaraenergo, Russia) was selected. As for the contact block, according to gained results of mathematical modelling a design of four-probe measuring transducer with one-side access to the object surface control (Fig. 2) has been specially developed.

Probes of round section in transducer are made of heat-resistant stainless steel of 95KH18 grade and then additionally hardened. Probe diameter is 5 mm. The distance between the internal potential (measuring) of probes is (60 ± 0.1) mm, and between current and corresponding potential probes is (10 ± 0.1) mm. These linear dimensions of probes obtained as result of mathematical modelling, are optimal in terms of sensitivity enhancement of the four-probe method.

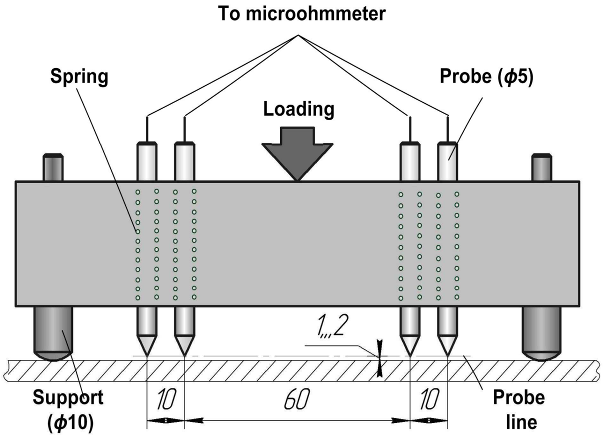
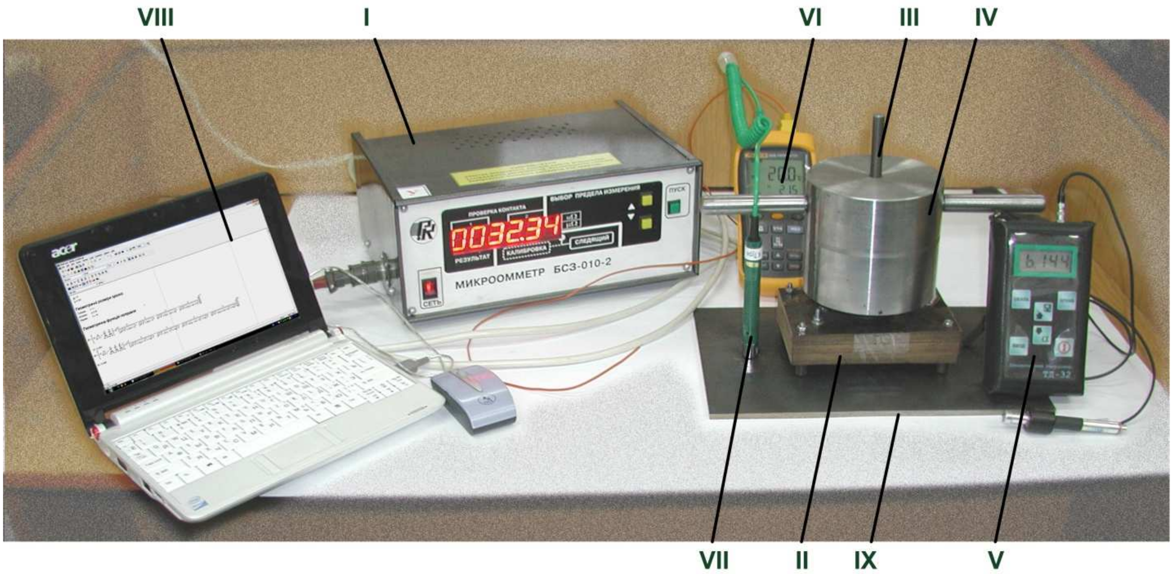


Figure 2 – Design of the measuring four-probe transducer

The corners of the frame contain four supports sprang with compression springs in the direction of the frame. Bar and probe springing allows self-positioning of the frame and probe line relatively to the surface due to its minor inequalities. In addition, probes and bars are designed with possibility of axial displacement relative to the frame that allows measurement on cylindrical surfaces (e.g. large diameter pipes). In order to establish a stable electrical contact of probes with the control object, loading barbell (10 ± 0.05) kg is placed on the integrated core of the transducer.

The benefits of the developed design of four-probe measuring transducer include: increased sensitivity, small operating measurement time, one-sided access to the control object surface possible. The patent of Ukraine was received for the design of the measuring transducer.

General view of the experimental setup for determination the physical and mechanical properties of steels is shown at Figure 3.



I – micro-ohmmeter BSZ-010-2; *II* – four-probe measuring transducer; *III* – core; *IV* – loading barbell; *V* – dynamic hardness tester TD-32; *VI* – digital thermometer Fluke 54-II; *VII* – contact thermocouple; *VIII* – portable computer; *IX* – controlled object

Figure 3 – General view of the information-measuring experimental unit

Technique for resistivity measurement using the developed measurement system is as follows. Four-probe measuring transducer with no-loading is set on the previously machined surface of control object and is clearly positioned relative to the control object surface. Using nuts on bars frame position with the probes are regulated so as to provide clearance 1–2 mm between the surface and control object (Fig. 2). It is necessary to keep conventional parallel line running through the end of the probe and the surface of control object. Then gradually impose loading barbell on the core. As a result, the springs on bars will compress, providing self-aligning of the frame on the surface of control object. When stable electrical contact with the control object and probes is set measurement system is ready for measurement. Adequacy of the equation (3) for calculating the resistivity of rectangular samples was tested on steel samples (grade 45) of different geometric dimensions [13]. Such design allows measurement of the electric resistivity on real-life pipelines.

Samples and Results

Methodology for experimental investigations aimed to evaluate physical and mechanical properties of steel was as follows. Made from real-life gas pipelines 14 samples of flat rectangular shape of low-alloy structural steel of ferrite-pearlite structure (Fig. 4) were selected. Metallographic investigations of samples were provided with the support of the National Metallurgical Laboratory NML (Jamshedpur, India).

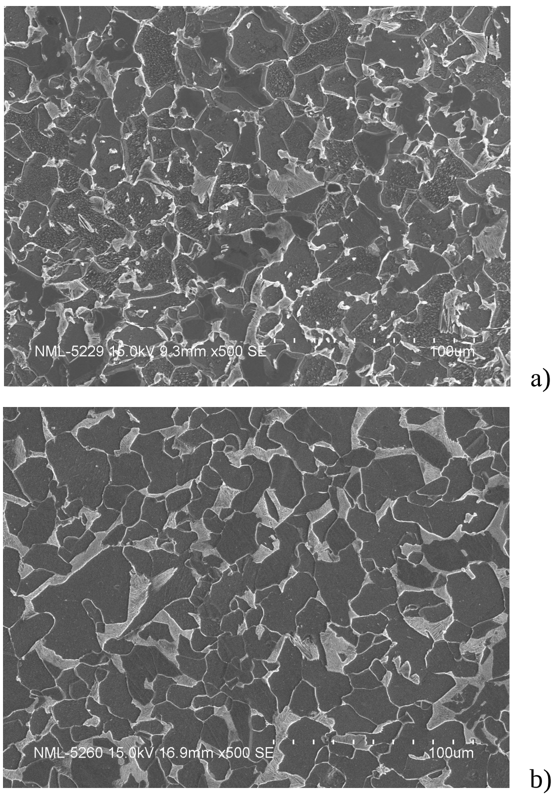


Figure 4 – Metallographic photos of the ferrite-pearlite structure samples on the example of samples 4 (a) and 14 (b)

Each sample was held with ten fold measurements of hardness and electrical resistance. Four-probe measuring transducer was placed in the centre of the sample, in which probes are placed along the centre line parallel to the longest side.

Measurements were conducted in the same laboratory conditions at temperature 20 ± 0,3 °C, which was registered by digital thermometer, equipped with a contact thermocouple. Measured values of electrical resistance readings taken from micro-ohmmeter BZS-010-2 (Fig. 3). Calculation of resistivity was carried out according to the formulas (2) and (3) on a laptop in MATLAB 7.0 environment. It should be noted, that electrical resistivity is temperature dependent characteristic, thus providing control in the real conditions, we should expect corrections in the resistance temperature coefficient.

Real values of yield strength were determined through destructive tests on tensile of standard proportional samples, made with full-size samples, at tensile machine according to ISO 6892. Averaged results of experiments are presented in Table 2.

Discussion

Figures 5 and 6 illustrate dependencies of yield strength with resistivity and hardness, respectively. Also, the figure shows approximation curves.

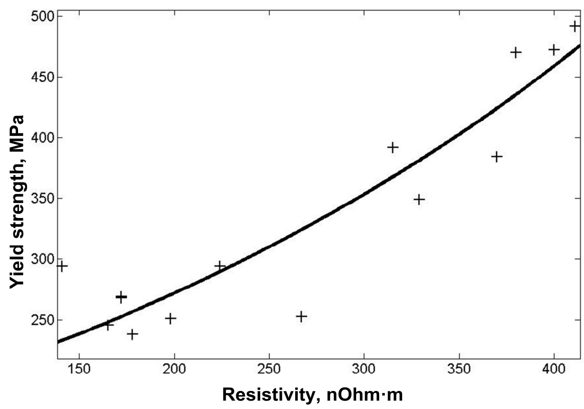


Figure 5 – Yield strength and resistivity dependence

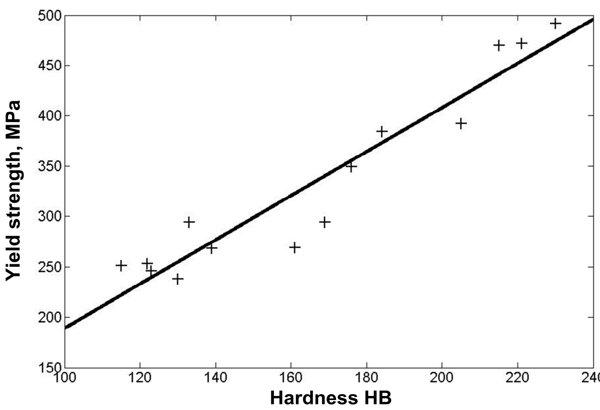


Figure 6 – Yield strength and hardness dependence

Table 2 – Results of experimental investigations

Sample No.	Dimensional relationships of samples to *S*			Geometric correction function ***f***, uniform units	Electrical resistance $\boldsymbol{R} \cdot 10^6$, Ω	Resistivity $\boldsymbol{\rho} \cdot 10^9$, Ω·m	Hardness Brinnel scale ***HB***	Yield strength $\boldsymbol{\sigma_T}$, MPa
	h/S	*a/S*	*b/S*					
1	1	34.6	9	0.2037	13.97	178	141.5	238
2	1.42	35	19.5	0.3156	10.00	198	114.9	251
3	1.47	33	3	0.1523	27.97	267	122.2	253
4	1.26	30	20	0.2870	18.25	329	175.6	349
5	1.63	30	16.4	0.3416	7.72	165	123.2	246
6	0.83	30	19.6	0.1990	11.28	141	133.1	294
7	1.17	30	19.7	0.2703	10.15	172	139.2	268
8	0.5	30	19.5	0.1216	22.54	172	160.6	269
9	0.7	40	27.6	0.1737	33.47	370	184.2	384
10	0.85	39.5	7.4	0.1638	21.83	224	168.7	294
11	1.1	40	5	0.1703	35.66	380	215.2	470
12	1.17	40	6.5	0.2059	24.36	315	234.8	392
13	1.88	40.3	18.4	0.3805	16.75	398	221.2	472
14	1.65	28	16.2	0.3436	18.92	411	218.6	492

Approximation parameters are following:

1) Dependence of yield strength and resistivity is approximated by function of $f(x) = a\exp(bx)$, where $a = 156.03$, $b = 2.69 \cdot 10^{-3}$. Relevant correlation coefficient is 0.69

2) Dependence of yield strength and hardness is approximated by function $f(x) = ax + b$, where $a = 2.03$, $b = -6.83$. Relevant correlation coefficient is 0.91.

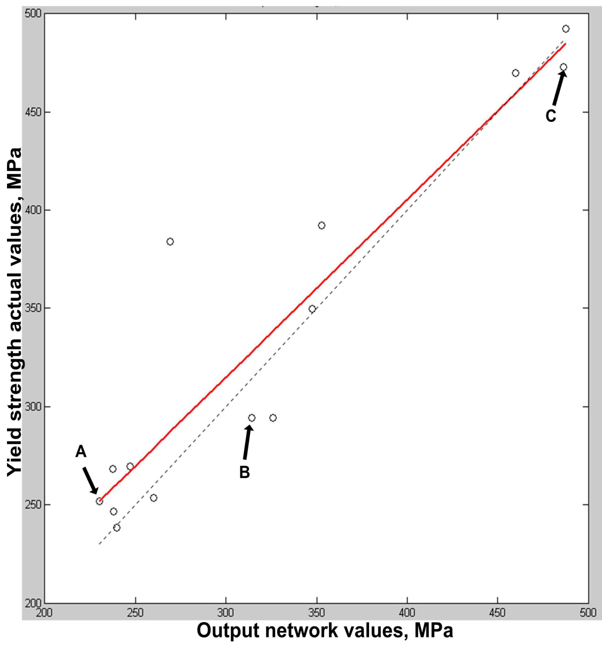
Dependence of yield strength with selected informative parameters has directly proportional character, which is consistent with previously established theoretical correlations [11]. In accordance with the developed neural network approach the method was applied to the gained experimental data because of the non-linear character of dependencies shown on Figures 5 and 6. Training set was composed of 11 sample data-sets as the testing set included 3 samples (2nd, 3rd and 13th, Table 2).

Training of neural networks in four different architectures (10×1, 12×1, 14×1, 16×1) was carried out for two input parameters (resistivity, hardness) and yield strength as output target. Neural network with architecture 10x1 was found to be the best for approximation of the yield strength as function of input parameters. Absolute error of neural network testing is 26 MPa or relative error of 2,5%. Results of the neural networks testing are shown in Table 3.

Table 3 – Neural network testing results for yield strength determination by electric resistivity and hardness values

Sample No	Yield strength real value, MPa	Yield strength neural network value, MPa
2	251	230
6	294	314
13	472	486

We conducted regression analysis in MATLAB 7.0 using function *postreg (t,x)* in order to estimate the accuracy of the network performance, where *t* is the target vector, *x* is the output network vector. This function compares the output network array with the target one (Fig. 7). The starting argument of this function is the correlation coefficient, which in our case is equal to *R* = 0.929. Absolute error of neural network testing is 26 MPa.



O – original network values,
- - - - line for the ideal case (R = 1),
—— line of regression for the network output vector (R = 0.929);
A, B, C – initial network values for samples not used during training

Figure 7 – Distribution of the network initial values relatively to the regression line

Results of experimental investigations using the developed prototype of a measurement system prove that the parameters complex of hardness and electrical resistivity can be used for evaluation of steel materials yield strength. These results also confirm previously obtained theoretical results concerning the choice of informative parameters.

Conclusions

An experimental unit was developed, which implements four-probe method for resistivity of steel measurements and repeated measurements on selected gas transmission pipeline samples were provided. Conversion of measured values of electrical resistance to the resistivity is performed by using the developed mathematical model.

Based on the obtained experimental results the existence and nature of dependence of yield strength with the chosen set of parameters (resistivity and hardness) have been established – directly proportional for both cases. It was found that this complex is characterized by the parameter correlation coefficients with yield strength (hardness – 0.91 and resistivity – 0.69).

Modern methods of statistical information processing (neural network) were used to approximate yield strength of pipeline steels as a function of parameters hardness-resistivity. The absolute error of neural networks testing was 26 MPa, the relative error test – 2.5%.

Acknowledgement

The study was supported by the funding of Ministry of Science and Education of Ukraine (project reg.no. 0111U002999).

References

[1] Plumbridge, WJ 2009, 'Fatigue resistance and structure (30 years on)', *Fatigue Fract Engng Mater Struct*, vol. 32, pp. 461–463.

[2] Bida, GV, Pochuev, ND, Stashkov, AN 2002, 'Nondestructive method for testing stress-strain properties of oil pipes', *Non-Destructive Testing*, vol. 38 (10), pp. 725–738 (in Russian).

[3] Karpash, OM, Molodetskyy, IA & Karpash, MO 2004, 'General overview of metals physical and mechanical properties evaluation methods', *Technical diagnostics and non-destructive testing*, vol. 2, pp. 18–22 (in Ukrainian with English abstract).

[4] Karpash, OM & Karpash, MO 2006, 'New neural-based method for evaluation of mechanical properties of steels': *proceedings of 9th European Conference of Non-destructive testing,* Berlin, p. 114.

[5] Horkunov, ES 1985, '*Interrelation between magnetic, electric properties and structure condition of thermally processed steels – as a basis for products strength properties determination by non-destructive methods*', Guidelines, Sverdlovsk, USSR Academy of Sciences (in Russian).

[6] Nahm, SH, Kim, KMYu, Kim, A 2002, 'Evaluation of fracture toughness of degraded Cr-Mo-V steel using electrical resistivity', *Journal of Material Science,* vol. 37 (16), pp. 3549–3553.

[7] Karpash, MO, Karpash, OM & Dotsenko, YR 2008, 'New challenges for mechanical properties evaluation of long-term used metallic structures': *proceedings of 4th International Symposium on Hydrocarbons and Chemistry*, Ghardaia (Algeria), p. 64.

[8] Bowler, N & Yongqlang, H 2005, 'Electrical conductivity measurement of metal plates using broadband eddy-current and four-point methods', *Measurement Science and Technology*, vol. 16 (11), pp. 2193–2200.

[9] Heaney, MB 1999, *Electrical Conductivity and Electrical Conductivity and Resistivity. The Measurement, Instrumentation and Sensors Handbook*, CRC Press LLC, Chapter 43.

[10] Dotsenko, YR 2010, 'Mathematical modelling of control resistivity materials by electric four-probe method', *Prospecting and Development of Oil and Gas Fields*, No. 1(34). pp.82–90 (in Ukrainian with English abstract). Available from: http://rrngr.nung.edu.ua/sites/rrngr.nung.edu.ua/files/journals/034/10dyrecm.pdf

[11] Karpash, MO, Dotsenko, YR & Kaprash, OM 2010, 'New methods for mechanical properties evaluation of steel structures with consideration of its microstructure': *proceedings of 10th European Conference of Non-Destructive Testing*, Moscow, part 2, pp. 270–271.

[12] Haykin, S 1999, *Neural networks. A comprehensive foundation*, Second edn, Prentice Hall, New Jersey.

[13] Karpash, OM, Dotsenko, YR, Karpash, MO & Mitra, A 2010, 'Experimental investigation for electrical resistivity measurement of metallic structures using four-point method': *proceedings of 5th International Symposium on Hydrocarbons and Chemistry (ISHC5)*, Sidi Fredj (Algeria), p. 112.

УДК 620.179

Визначення механічних характеристик трубопроводів неруйнівним методом з урахуванням мікроструктурних змін

М.О. Карпаш, Є.Р. Доценко, О.М. Карпаш*

Івано-Франківський національний технічний університет нафти і газу;
15, вул. Карпатська, м. Івано-Франківськ, 76019, Україна

Існуючі мережі трубопроводів для транспортування нафти і газу перебувають в експлуатації десятиліттями, що в результаті призводить до суттєвих деградаційних процесів. Наведено результати експериментальних досліджень питомого електричного опору сталей газопроводів за допомогою спеціально розробленого пристрою, що реалізує чотириконтактний метод. Використано багатопараметровий підхід, за якого нейронні мережі застосовуються для нелінійної апроксимації границі плинності трубопроводів як функції твердості та питомого електричного опору. Для розрізнення мікроструктури використовувались спеціально термічно оброблені сталеві зразки, а також зразки, взяті із тривалоексплуатованих трубопроводів. На всіх зразках було виконано руйнівні дослідження границі плинності, результати яких використовувались як базові. Показано, що чотириконтактний метод може використовуватись для всієї металоконструкції, оскільки її реальні розміри не впливають на результат вимірювання за виключенням зведеної товщини частини зразка, в якій густина струму сягає найбільших значень та визначає значення питомого електричного опору. Комбіноване вимірювання твердості та питомого електричного опору з подальшим обробленням нейронними мережами дає можливість досягти точності 26 МПа з визначення границі плинності реальних трубопроводів.

Ключові слова: *границя плинності, нейронні мережі, питомий електричний опір, твердість, трубопроводи.*