New Neural-based Method for Evaluation of Mechanical Properties of Steels

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Abstract. The problems of usage of combined measurement method for several material parameters set (hardness and thermal conductive parameter) to evaluate mechanical properties of metalwork materials. The results of comparative investigations to establish the dependence between several non-destructive parameters and yield strength of the lifting pipe material are given.

Introduction

The problem of actual mechanical properties evaluation is a very important for wide range of structures and its solution will lead to its real technical state assessment in order to prolong exploitation period. This problem is considered to be provisional component of technological safety of Ukraine [1] at the state level.

1 Theoretical Background

1.1 Problem Description

The common base of metalwork used in basic branches of Ukrainian economy is near 35 million tons. The rated resource of more than 50% of the structures is already expired; the other part is very close to similar condition. During the exploitation period a number of factors influence on the structures (high pressures and temperatures, local overloads, aggressive environments) what results in microstructure degradation, mechanical properties alteration and afterwards in defect initiation and growth [2].

From economic and resource saving points of view the most effective way to control changes of mechanical properties is its non-destructive evaluation (NDE).

There are several main methods of NDE: ultrasonic [3,4], magnetic [5,6], eddy-current and electrical. Analysis of these methods showed that none of them has strict theoretical background which could provide establishment of analytic dependences between mechanical properties and informative parameters that can be measured. Obviously the informative parameters should be structure sensitive and measurable.

Thus the objective of the paper is the development of new method for mechanical properties evaluation using new informative parameters.

1.2 Complex Approach

First of all the analysis of normative documents for steels was done. The main idea of investigation was to select new informative parameter among physical properties of steel set by relevant regulations. Second, several parameters were chosen to be considered to solve the stated problem. From technological point of view yield strength was selected as target mechanical property in our work. The stated problem can be referred as non-linear multiparameter approximation problem. Neural networks are very suitable tool for solving such problems in material characterization [7].

Reference data for steel grades 440, 630, 431, UR52N+, 420, 2205, 416, 409, 3CR12, 304, 310, 321/347, 430, 430F, S30815 which mechanical and physical properties were defined according to ASTM standards were used in theoretical investigations to determine optimal complex of parameters for yield strength evaluation. Physical properties which were investigated are as follows: hardness, density, heat capacity, thermal conductivity, heat expansion coefficient and resistivity. Graph-analytic, correlation and neural network based analysis showed that such parameters as hardness, thermal conductivity and resistivity enable yield strength evaluation to be done with mean error less than 3%.

No information about interrelation between thermal conductivity and yield strength was found and thus requires experimental proof.

1.3 Analysis of Measurement Capability

Hardness measurement. Based on the conditions of theoretical investigations hardness should be measured in the range of 100-400 HB with accuracy of ±5 HB. For this purpose commercial dynamic hardness meters can be used.

Resistivity measurement. Resistivity measurement should be done with the accuracy of ±10 nOm·m. Contact measurement schemes can not be applied under the field conditions. Non-contact (eddy-current) methods don't give the best fit for ferromagnetic materials because of simultaneous influence of resistivity and magnetic permeability on eddy-current signal. Therefore we decided to skip resistivity measurement keeping in mind that thermal conductivity is generally correlated to electrical conductivity by the Wiedemann-Franz law for metals and intermetalics [8].

Thermal conductivity measurement. To evaluate the possibilities of thermal conductivity measurement the appropriate mathematical modeling was done.

1.4 Informative parameter – characteristic of thermal conductivity

Considering on inexpedient and essential obstacles related with measurement of real thermal conductivity values the informative parameter which characterizes thermal conductivity should be found.

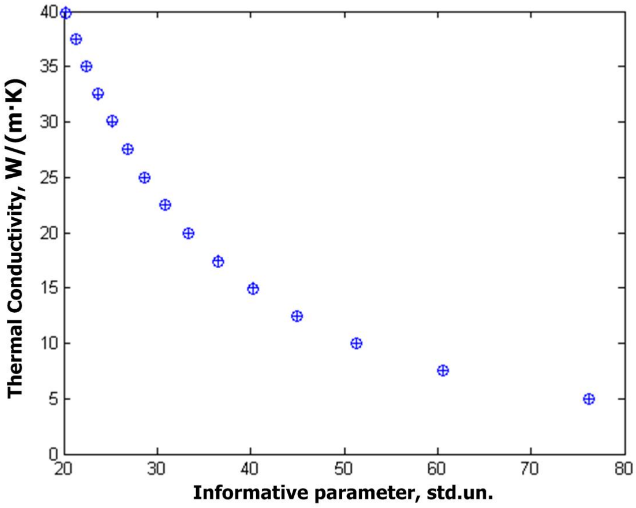
The proposed parameter characterizes heat quantity that flowed through the fixed distance (5 cm) in 60 seconds. Modeling investigations showed that proposed parameter correlated to real values of thermal conductivity – fig.1.

The dependence can be approximated by function:

$$k(M) = a \cdot \exp(b \cdot M) + c \cdot \exp(d \cdot M)\,, \qquad (1)$$

where factors are as follows: *a = 135.7, b = -0.09126, c = 29.97, d = -0.02389*.

Approximation mean square error came to *0.07136*.



+ - real values; **O** – approximated values

Fig.1 Thermal conductivity and informative parameter dependence

2 Experimental Investigations

2.1 Experimental setup

The experimental setup was developed and produced for practical proof of the proposed evaluation method. Overview of the setup is given at fig.2.

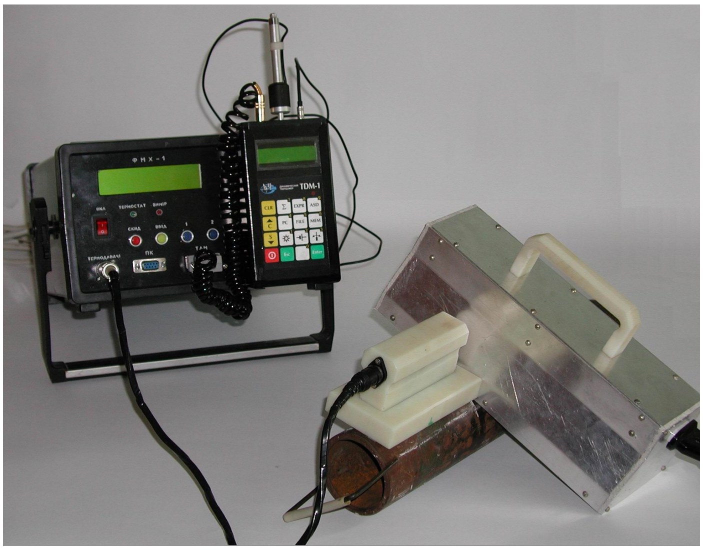


Fig.2. Experimental setup

Experimental setup consists of: PIC-based signal processing unit, temperature measuring unit (six thermistors arranged in line with 1 cm step), dynamic hardness meter and heating unit (with ceramic infrared heater).
Measurement scheme using the experimental setup is shown at fig.3.

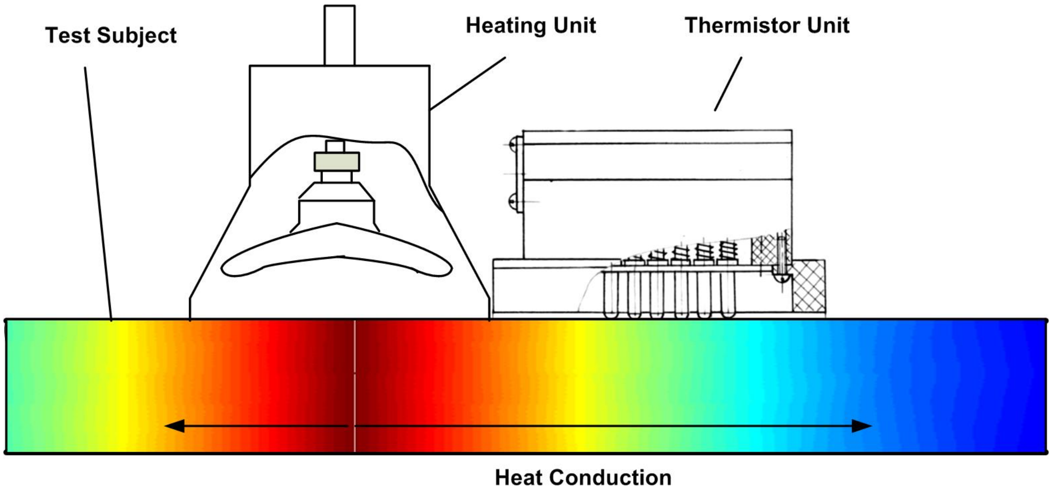


Fig.3. Positional relationship of heating and thermistor unit on the surface of test subject

2.2 Lifting Pipe Samples Examination

Experimental proof of the developed method was done using samples of lifting pipes. It is known that cost of all pipes make up to 30% of total cost of the whole equipment installed at oil and gas well. During the makeup of lifting string it is of vital importance to ensure that actual mechanical properties of pipes are qualified according to normative documents. Nowadays there are only few specialized devices which make possible only classification of pipes into durability grades [9,10].

Test procedure of the experimental investigations lays in the following. A set of 13 lifting pipe samples with previously measured mechanical properties according to GOST 10006-80 was selected. Wall thickness of all samples – 5.5 mm, standard diameter – 73 mm. Yield strength range of selected samples – 320-760 MPa.

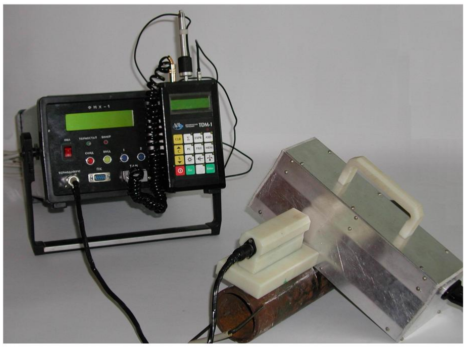
The measurements using the following devices were done for comparative study of the proposed method:

- dynamic hardness meter TDM-1 (RPC ‘Ultracon-Service’, Kyiv – fig.4,a);
- coercive force meter KRM-CK (RPC ‘SNR’, Harkiv – fig.4,b);
- experimental setup – fig.4,c;
- specialized device for mechanical properties evaluation of lifting pipes SIGMA-T10.1 (RPC ‘Zond’, Ivano-Frankivsk – fig.4,d).

a)

b)

c)



d)

a) – *hardness meter TDM-1;* **b)** – *coercive force meter KRM-CK;*
c) – *device SIGAM-T10.1;* **d)** – *experimental setup.*

Fig.4. Technical means used in comparative studies

Each sample was marked with grid formed of four generatrixes and three cross-sections (12 measurement points in total) to minimize influence of various factors (material anisotropy, edge effects etc). In every point 5 simultaneous measurements were done using all the devices.

Averaged experimental results are given in Table 1.

Table 1. Experimental results

sample №	Yield strength YS, MPa	Hardness *HB*	Coercive force H_c, A/m	SIGMA-T10.1 readings *S*, MPa	Informative parameter *M*, std.un.
1	*2*	*3*	*4*	*5*	*6*
1	320	169.5	2.59	571.8	541.2
2	470	193.3	7.46	559.6	534.2
3	490	201.3	5.86	574.8	530.9
4	581	203.1	8.43	574.7	518.4
5	588	210.9	7.76	568.9	516.8
6	600	211.1	9.28	656.6	514.4
7	600	227.5	6.73	616.9	516.1
8	610	199.1	9.64	564.2	518.7
9	629	226.6	12.50	590.8	510.3
10	668	235.3	10.85	662.3	500.8
11	682	240.3	7.49	671.5	496.8
12	700	261.8	8.34	633.5	484.5
13	760	270.0	7.36	622.3	483.9

Correlation coefficients of yield strength *YS* and measured parameters (hardness *HB*, coercive force *Hc*, SIGMA-T10.1 readings *S* and informative parameter *M*) are given in Table 2.

Table 2. Correlation Coefficients

	HB	*Hc*	*S*	*M*	*YS*
HB	1	0.385	0.655	-0.865	0.910
Hc		1	0.267	-0.439	0.624
S			1	-0.689	0.609
M				1	-0.895
YS					1

Correlation analysis showed that yield strength correlates evidently to hardness and informative parameter. Minus for heat conductive informative parameters indicates that its dependence on yield strength is inversely proportional. In general all values of correlation coefficients don't reach high values (close to 1) what can be explain by nonlinear character of all dependences.

Afterwards investigations were aimed at selection of optimal parameter set that would enable the most accurate evaluation of yield strength. To solve this nonlinear multi-parameter approximation problem neural networks were decided to be applied [11].

Neural network with one hidden layer was trained for this yield strength approximation as a function of two, three or four measured parameters. The idea of selection is to compare test results of different trained networks. Optimum criteria in this case are minimal quantity of input parameters and the least error of yield strength evaluation.

Based from four measured parameters (*HB, Hc, S, M*) were formed *11* sets of two, three and four parameters which represented all possible combinations.

After the testing of the trained neural networks on every parameter set as input the following results were obtained and formed into table 3 according to the optimum criteria.

Table 3. Selection of optimal parameter set

#	Input parameter quantity	Input parameters	Testing error	
			MPa	%
1	**2**	*HB, Hc*	31.1	7.1
2		*HB, S*	11.6	2.4
3		<u>*HB, M*</u>	<u>9.6</u>	<u>2.2</u>
4		*Hc, S*	45.3	10.3
5		*Hc, M*	24.5	5.6
6		*S, M*	10.9	2.5
7	**3**	*HB, Hc, S*	25.8	5.9
8		*HB, Hc, M*	24.9	5.7
9		<u>*HB, S, M*</u>	<u>2.7</u>	<u>0.7</u>
10		*Hc, S, M*	12.5	2.8
11	**4**	<u>*HB, Hc, S, M*</u>	<u>7.8</u>	<u>1.8</u>

Based on the results shown in Table 3 the following conclusions can be done:

1) the increase of input parameters quantity commonly leads to the raise of accuracy of yield strength evaluation;

2) coercive force included into parameter set worse capability of neural networks to evaluate yield strength;

3) the least evaluation error criterion gives the following set of parameters: hardness, informative parameter, SIGMA-T10.1 readings;

4) in case of the least error and minimal parameter quantity criterions application as the most optimal set should be determined as hardness and informative parameter;

The dependence of yield strength on the input parameter set is in the structure of trained neural network. The special algorithm was developed in order to visualize this dependence for the case of optimal set of parameters (hardness and informative parameter) – fig.5.

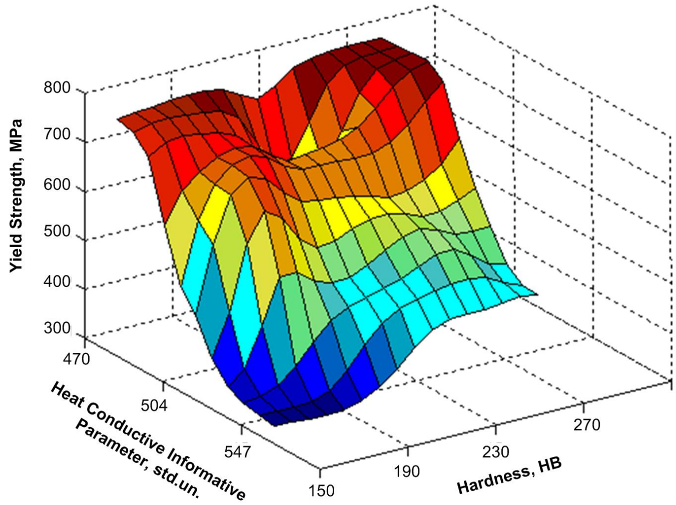


Fig.5. Yield strength dependence of hardness and informative parameter

Analysis of the obtained graph showed that yield strength is directly proportional to hardness and inversely proportional to heat conduction informative parameter what is confirmed by values of correlation coefficients in table 2.

2.3 Main pipelines samples investigation

Using the described technique the informative parameter was measured for several samples made of main pipelines with standard diameter of 1000 mm (steel grade 17GS) with different exploitation periods – 15 years and new. The results of such investigations indicate that after exploitation informative parameter decreased by 12%, hardness – by 10%. These results confirm the common principals of steel degradation processes [12,13] – plasticity decrease appears in yield and tensile strength approachment.

3 Conclusions

The results of theoretic and experimental investigations allowed to propose new original parameter for mechanical properties evaluation – heat conductive informative parameter. The new method for yield strength evaluation which is based on the dependence on the set of parameters (hardness and informative one) and neural networks was developed. The experimental proof of the developed method was done on the samples of lifting pipes. The obtained yield strength evaluation accuracy is 2.2%.

The developed evaluation method can be propagated for inspection of other types of structures and materials (e.g. main pipelines).

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