"Instrumentation Engineering, Electronics and Telecommunications – 2019"
Proceedings of the V International Forum (Izhevsk, Russia, November 20–22, 2019)

DOI: 10.22213/2658-3658-2019-76-84

Change in the Acoustic and Elastic Properties of the Cylindrical Steel Specimens during the Tensile

O. V. Murav'eva, S. V. Len'kov, A. A. Nagovitsyn, A. F. Basharova

Kalashnikov Izhevsk State Technical University, Izhevsk, Russian Federation
E-mail: pmkk@istu.ru

Received: August 10, 2019

Abstract. The paper presents the results of an experimental study of the effect of tensile stresses in the elastic and plastic regions on the velocities of longitudinal and transverse waves and the Poisson's ratio for cylindrical samples of steel 40X with different heat treatment. A multiple mirror-shadow method with the use of specialized electromagnetic-acoustic transducers, which provides high accuracy and reliability of measurements due to detuning from the quality of the acoustic contact and the geometry of the sample, as well as the possibility of registering a series of multiple reflections across the sample section, is used. It is shown that the velocities of acoustic waves is minimal, and the Poisson's ratio is maximal for the sample obtained by quenching. The behavior of the curve of the transverse wave velocity change is identical to the transverse deformation of the sample, while the sensitivity of the transverse waves to mechanical stresses is maximal due to the matching with the direction of the applied load. The greatest sensitivity to stress is characteristic of the samples after tempering and normalization. After removal of the load and subsequent «recovery», there is an uneven distribution of the Poisson's ratio along the length of the sample.

Keywords: ultrasound, transverse wave, longitudinal wave, tensile stresses

INTRODUCTION

During the exploitation, many products made of rolled bars, for example, pumping rods experience tensile loads, are affected by tensile stresses, the occurrence of which leads to the accumulation of damage and critically affects the life service of the product and its characteristics. For testing the stress there are used strain state of products, as a rule, magnetic structuroscopy [1-4] and ultrasonic methods based on the measurement of the characteristics of elastic waves in a tested environment [5-13]. The advantages of acoustic methods based on the measurement of the characteristics of elastic waves in a testing environment include the ability to determine surface and internal stresses, accumulation of micro-damage in the volume of the material; multiparameter of testing in favor of the variety of types of waves used and recorded parameters; efficiency of testing, high resolution capability and the ability to measure directly on the tested objects during operation. Due to the use of elastic waves, it is possible to obtain the most reliable connections with the structural and mechanical parameters of the materials of the products. The method of estimating tensile stresses is based on the phenomenon of acoustoelasticity, which is the quotient between the velocities of ultrasonic waves and mechanical stresses. The method of acoustoelasticity is standardized as a method of testing of internal mechanical stresses and therefore differs significantly from diagnostic methods that use electromagnetic properties of metals. Also, the exploitation and technological characteristics and deformation behavior of materials are influenced by the Poisson's ratio which associated with the strength and crack resistance and anisotropy of the mechanical properties of the rolled products [14–21].

The aim of the work is to study the effect of the tensile uniaxial load in the elastic and plastic areas, as well as study the effect on the velocity of longitudinal and transverse acoustic waves after loading cylindrical samples of steel 40KH and study Poisson's ratio.

Proposed Approach

As an object of research, there were used samples of 40KH-steel bars according to GOST 4543-71, which used for the manufacture of critical parts of oil-producing equipment – rods-billets of pumping rods and shafts of centrifugal pumps. To evaluate the effect of tensile stresses on the measured characteristics of acoustic waves, samples with a diameter of 14 mm in the state of delivery and subjected to additional heat treatment and mechanical properties of the studied samples are presented in the Table 1. The hardness of the samples was determined using the hardness tester Novotest T-UDZ. The chemical composition of 40KH steel samples was determined by using a portable analyzer of metals and alloys – XMET – 5000: C – 0.4, Cr – 0.8, Si – 0.2, Mn – 0.5.

Table 1. Heat treatment and reference mechanical properties of samples of 40KH-steel

No	Type of the heat treatment	Stress limit, σ_S, MPa	Yield stress, $\sigma_{0.2}$, MPa	Elongation, δ, %	Hardness HB
#1	Delivery condition: heat quenching 860°C, oil, tempering 650°C (improvment)	850	730	19.0	306
#2	Heat quenching, 850°C, oil	1400	1320	8.0	441
#3	Heat quenching, tempering, 570°C	1050	960	17.0	335

To determine the velocities of elastic waves, there was used multiple echo-pulse method with using electromagnetic acoustic (EMA) principle of launching-receiving of acoustic waves which provides high accuracy and reliability of measurements by detuning from the quality of the acoustic contact and the possibility of registering a series of multiple reflections across the sample section [22–24].

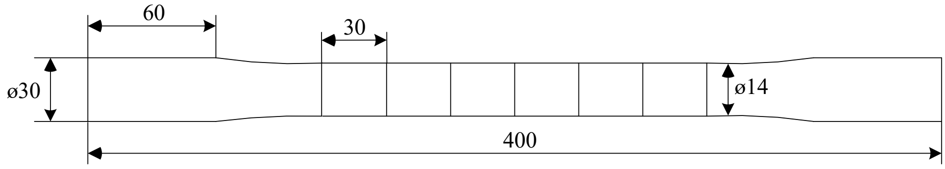


Figure 1. Sample form for investigations and marking for measurement after tensioning

The samples were stretched progressively at intervals of 10 kN until the yield strength was reached by the Instron 300DX test machine. To study the velocities of volume waves, an electromagnetic-acoustic structurescope (SEMA) was used [23-25], which implements the mirror-shadow method on multiple reflections, the functional scheme of which is shown in

Figure 2,a. Polarization of the wave types which was used in the carried coordinate system is shown in Figure 2,b. The axial polarization of the transverse waves U_z corresponds to the direction of loading, the radial polarization of the longitudinal waves U_r is oriented across the tensile load. Launching and receiving of longitudinal and transverse waves were produced in all radial directions along the cross section of the sample there were used specially developed EMA-converters of longitudinal and transverse waves of the split type presented in Figure 3 [26]. For registration and further processing of the received series of multiple reflections the specialized software Prince [27] was used. Typical waveforms of a series of multiple reflections of the transverse wave along the rod diameter and selected fragments of pulses at 7 reflection without load and at a load of 1600 MPa, the fraction of the sample #2 are shown in Figure 4.

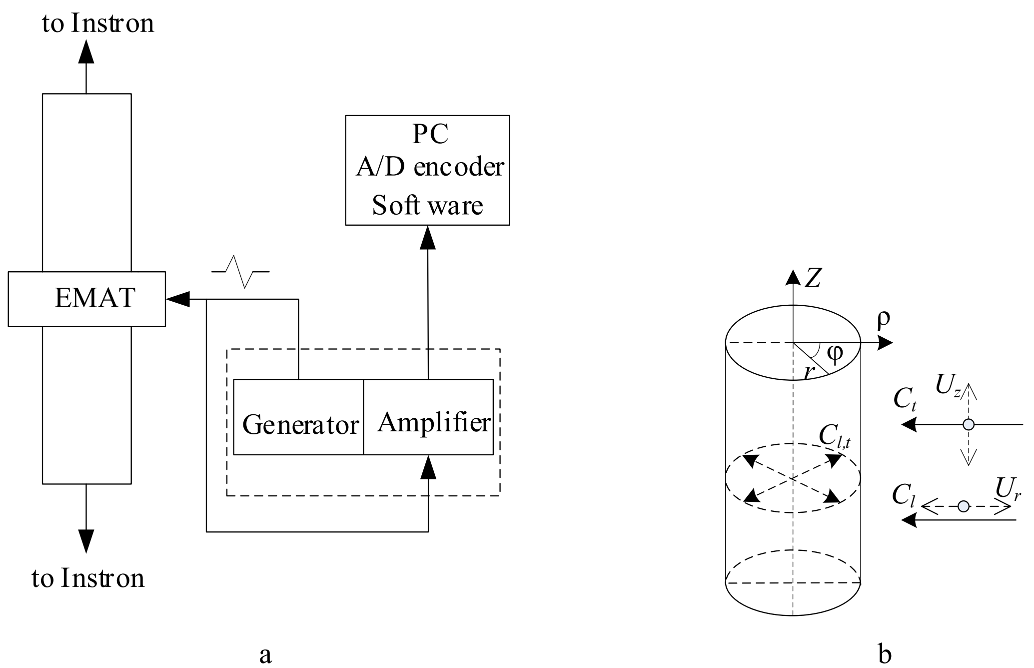


Figure 2. Sample loading and registration scheme (a), carried coordinate system and polarization of the waves used (b)

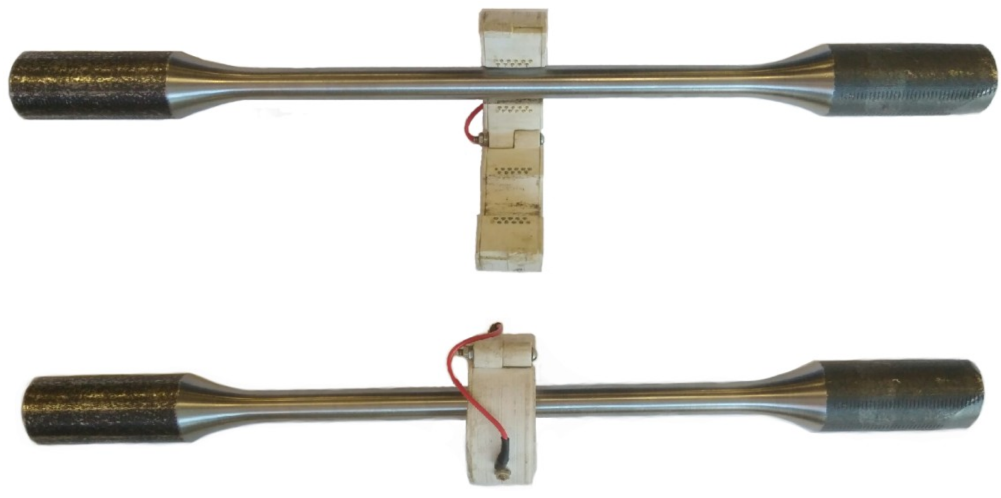


Figure 3. Photo of detachable EMAT of longitudinal waves which is set in the centre of the sample

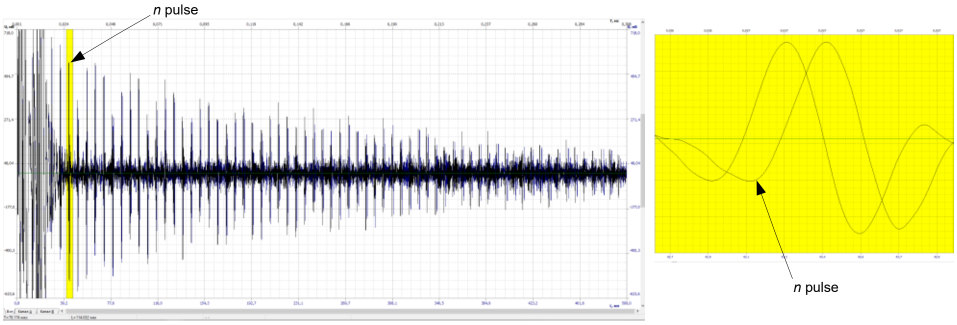


Figure 4. Typical oscillograms of a series of multiple reflections of a transverse wave along the rod diameter and pulses at 7 reflection without load and at a load of 1600 MPa

The velocities of transverse and longitudinal waves were calculated using the following formulas:

$$C_{l,t} = \frac{d \cdot n}{\Delta t_n}, \tag{1}$$

where d is the average diameter of the sample at each loading step, Δt_n is the time of the n-th reflected pulse in the transverse t and longitudinal l waveforms.

The influence of the number of recorded reflections n on the difference of received tense Δt_n is illustrated in Figure 5. There is a close to linear dependence, in fact the minimum deviations are in the zone of large values n. Significant deviations in the region of small n are due to the influence of a powerful probing pulse on the measurement accuracy.

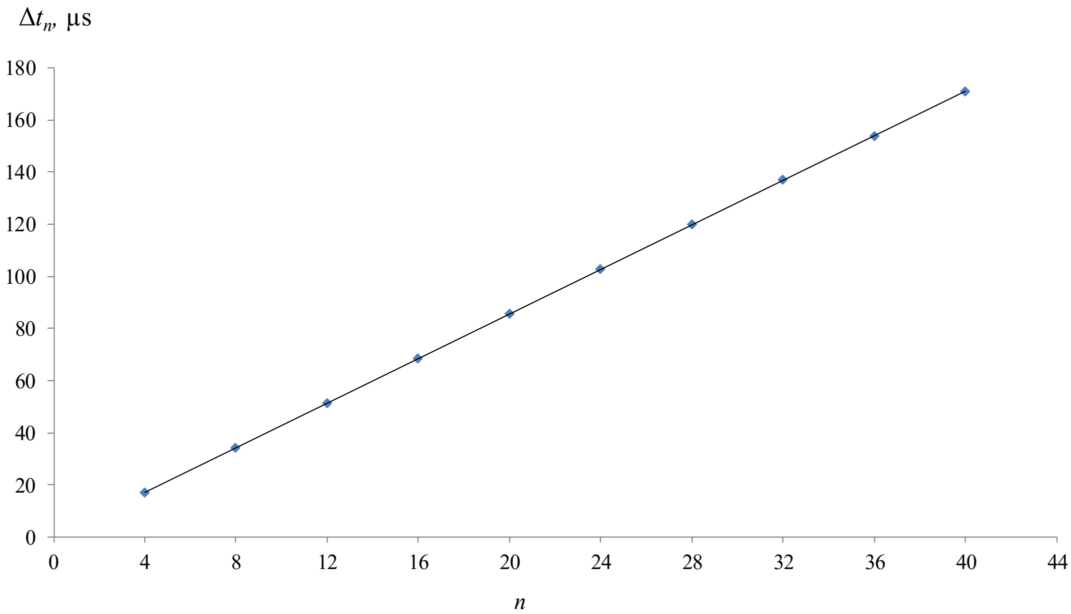


Figure 5. Graph of the dependence between the number of reflections and the time difference between them

Due to the high sampling rate of the used equipment (100 MHz), the subsequent interpolation of the signal is produced by using specialized software, as well as due to the possibility of measurements on long-range reflections, high accuracy of determining the speed of propagation of acoustic waves (0.5 m/s or 0.01%) with the accuracy of determining the diameter of the sample 50 microns.

The degree of influence of mechanical tensile stresses on the speed of transverse and longitudinal waves can be estimated by the coefficients of acoustoelastic coupling, calculated by the formulas:

$$\beta_{zz}^{c} = \frac{\Delta C_t}{C_{t0} \cdot \sigma_{zz}}, \tag{2}$$

$$\beta_{zr}^{c} = \frac{\Delta C_l}{C_{l0} \cdot \sigma_{zz}}, \tag{3}$$

where $\Delta C_{l,t}/C_{l,t(0)}$ is the relative velocity change under loading, σ_{zz} is the applied load.

In the evaluation of the elastic modulus (Poisson’s ratio ν) its functional connection is used with the propagation velocity of volumetric (longitudinal and transverse) waves. When a sample is emitted in one section using longitudinal and transverse waves, it is possible to determine the Poisson's ratio regardless of the sample diameter [19]:

$$\nu = \frac{C_l^2 - C_t^2}{2\left(C_l^2 - C_t^2\right)^2} = \frac{1 - 2\gamma^2}{2\left(1 - \gamma^2\right)}, \tag{4}$$

where $\gamma^2 = \frac{C_t^2}{C_l^2} = \frac{\Delta t_l^2}{\Delta t_t^2}$ – is the ratio of the velocities of the transverse and longitudinal waves, proportional to the ratio of their time propagation.

The proposed method of determining the Poisson's ratio by measuring the difference between the travel times of two types of waves in one section allows to adjust from a number of interfering factors that occur when measuring the absolute values of velocities. Calculations show that the indirect error of the absolute value of the Poisson's ratio does not exceed 0.01 % (that is, up to the fifth significant digit after the decimal point).

Results and Discussion

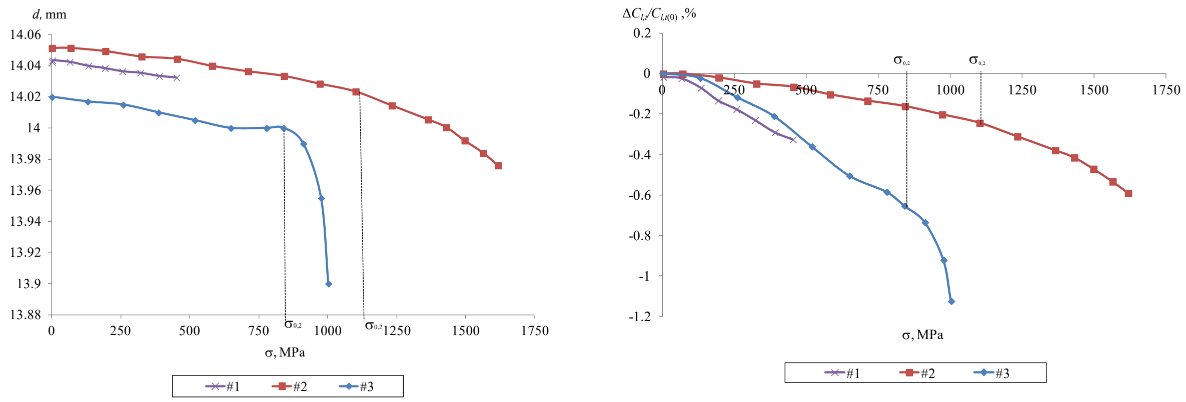
The values of longitudinal and transverse wave velocities and Poisson's ratio in 40KH steel samples with different heat treatment options are presented in Table 2. For the sample #2 obtained by quenching, having a martensite structure with a maximum degree of distortion of the crystal lattice, the propagation velocity of longitudinal and transverse waves is minimal, and the Poisson's ratio describing the resistance to transverse deformations is maximal. Subsequent tempering (sample #3), and especially softening treatments such as normalization (sample #1), leading to the most equilibrium ferrite-pearlite structures lead to an increase in the velocity of ultrasonic waves and a decrease in the Poisson's ratio.

Table 2. Longitudinal and transverse wave velocities and Poisson's ratio in the samples under study before loading

Sample number	C_l, m/s	C_t, m/s	ν
#1	5940	3251	0.286
#2	5881	3193	0.291
#3	5918	3232	0.287

It should be noted that the mechanical properties - hardness, strength and yield strength, elongation (Table 1) also correspond to the structural state of the samples and satisfactorily correlate with the propagation velocities of transverse and longitudinal waves. The wave speed decreases with increasing strength and fluidity, hardness of the bars and increases with increasing plasticity, elongation.

The effect of axial tensile stresses on the change in the mean diameter and the relative value of the transverse wave velocities for the samples are illustrated in Figure 6. With increasing tensile load there is a significant linear decrease in the velocity of transverse waves with axial polarization (along the direction of the load). The behavior of the transverse wave velocity change curve is identical to the transverse deformation of the sample. At the same time, the sensitivity of transverse waves to mechanical stresses is maximal due to the coincidence with the direction of the applied load. The greatest sensitivity to stress is characteristic of samples #1 and #3. It should be noted that in the transition from the elastic deformation zone to the plastic deformation zone there is nonlinearity in the behavior of the curve, while the acoustoelasticity coefficients increase. The change in the velocity of radially polarized longitudinal waves is practically unchanged (within the measurement error). The values of acoustoelastic coefficients of transverse waves for the studied samples in the elastic and plastic regions are summarized in Table 3.



a b

Figure 6. Dependence of diameter of samples (a) and also their relative change of speed of a transverse wave (b) on loading

Table 3. Acoustoelastic velocity coefficients for transverse wave β,1/TPa

Sample number	For	
	Elastic deformation area	Yield area
#1	–6.2	–7.6
#2	–2.2	–6
#3	–5.8	–10,6

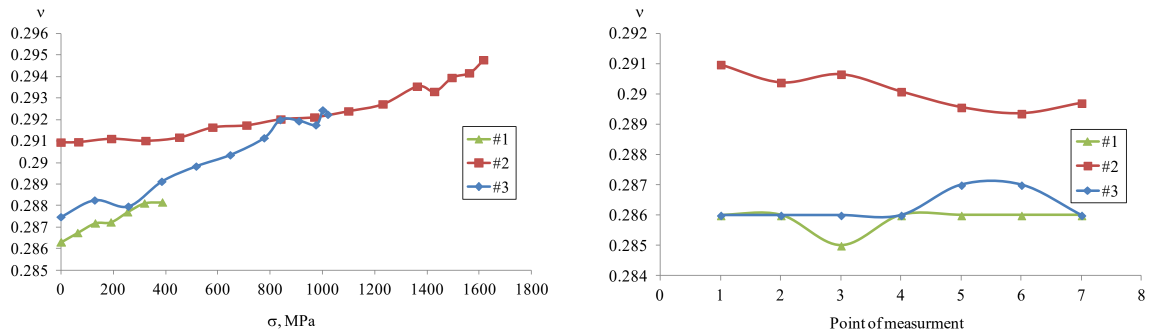
Table 4 presents the results of measuring the diameters and velocities of the volume waves at the time of full unloading and some time after the tensile experiment (the process of "recovery" of the sample). There is a slight increase in the diameter for the samples #1 and #2 (within 0.07 %) with an unexpressed yield point in the region. For the sample #3 with a strongly marked yield point, the largest increase in diameter (within 0.5 %) is observed due to stress relief during the "recovery". Note that the velocities of the longitudinal waves do not change significantly (0.05–0.1%), while the change in the velocity of the transverse waves reaches 0.5 %, and the Poisson's ratio is 1 % for the sample #2.

The curves illustrating the change in the Poisson's ratio with increasing load and its decrease during unloading, as well as its distribution along the length of the studied samples after the process of "recovery" of the sample are shown in Figure 7. There is a linear increase in the Poisson's ratio with an increase in the tensile load, which is least expressed for the #2 sample obtained by quenching, and more expressed for the #1 and #3 samples after normalization and high tempering.

It should be noted that the distribution of the Poisson's ratio along the length of the sample after removal of the load and subsequent "recovery" is sufficiently uneven and reaches 0.5 % for the hardened sample #2 and 0.35 % for samples #1 and #3. The latter indicates a significant uneven distribution of the stress-strain state, especially under plastic deformation.

Table 4. Diameters, velocities of volume waves and Poisson's ratios of the studied samples after load removal and after "recovery"

Sample number	at the end of tensioning				after "recovery"			
	d, mm	C_l, m/s	C_t, m/s	ν	*d*, mm	C_l, m/s	C_t, m/s	ν
#1	14.01	5934	3250	0.286	14.02	5937	3251	0.286
#2	14.00	5880	3183	0.293	14.01	5885	3200	0.290
#3	13.88	5904	3224	0.287	13.95	5910	3235	0.286



a b

Figure 7. The dependence of the Poisson's ratio on the load (a) and its distribution along the length of the test sample after loading (b)

Results

Thus, the developed non-contact EMAT-technology is a thin tool in evaluating the structural and stress-strain state of the bar. The conducted studies have shown the possibility of using the following structural-sensitive factors for the structuroscopy and evaluation of the stress-strain state of steel bars: absolute values of longitudinal and transverse velocities and Poisson's ratio, their change in the process of mechanical loading, and uneven distribution along the length of the sample and acoustoelastic velocity coefficients.

Due to the detuning from the quality of the acoustic contact and the possibility of obtaining a series of multiple reflections, high accuracy, reproducibility and reliability of acoustic structure detection methods are ensured.

It is shown that depending on the type of heat treatment, the velocities of transverse waves vary in the range of 1 %, longitudinal waves – 2 %, and the Poisson's ratio – 1.7 %.

The acoustoelasticity coefficients for transverse wave velocity for the sample in the quenched state were −5.8 1/TPa in the elastic deformation region and −10.6 1/TPa in the yield region.

This work was carried out under the State Task of the Ministry of Education and Science of Russian Federation for Kalashnikov Izhevsk State Technical University in 2017–2019 "Organization of Scientific Investigations"(Project No. 5705.2017/VU), and under the project implemented with funding from FSBEI of Higher Education Kalashnikov ISTU (Project No. 12.06.01.18 MOV), using Universal Scientific Unit "Information-measuring complex for evaluation acoustic properties of materials and products" (reg. No. 586308).

REFERENCES

1, Gorkunov, E. S., Zadvorkin, S. M., Goruleva, L. S., Makarov, A. V., & Pecherkina, N. L. (2017). Structure and mechanical properties of a high-carbon steel subjected to severe deformation. *The Physics of Metals and Metallography*, *118*, 1006–1014. doi: 10.1134/S0031918X17100076

2. Gupta, B., Uchimoto, T., Ducharne, B., Sebald, G., Miyazaki, T., & Takagi, T. (2019). Magnetic incremental permeability non-destructive evaluation of 12 Cr-Mo-W-V steel creep test samples with varied ageing levels and thermal treatments. *NDT and E International 104*, 42–50. doi: 10.1016/j.ndteint.2019.03.006

3. Hu, B., & Yu, R. (2016). Variations in surface residual compressive stress and magnetic induction intensity of 304 stainless steel *NDT and E International 80*, 1–5. doi: 10.1016/j.ndteint.2016.02.003

4. Ding, S., Tian, G., & Sutthaweekul, R. (2019). Non-destructive hardness prediction for 18CrNiMo7-6 steel based on feature selection and fusion of Magnetic Barkhausen Noise. *NDT and E International 107*, 102138. doi: 10.1016/j.ndteint.2019.102138

5. Ivanova, Y., Partalin, T., & Pashkuleva, D. (2017). Acoustic investigations of the steel samples deformation during the tensile. *Russian Journal of Nondestructive Testing*, *53*(1), 39–50. doi: 10.1134/S1061830917010077

6. Mohammadi, M., & Fesharaki, J. J. (2019). Determination of acoustoelastic/acoustoplastic constants to measure stress in elastic/plastic limits by using LCR wave. *NDT and E International 104*, 69–76. doi: 10.1016/j.ndteint.2019.04.003

7. Zuev, L. B., Barannikova, S. A., Li, Y. V., & Zharmukhambetova, A. (2018). On numerical estimates of the parameters of localized plasticity during metal tension. *Tomsk State University Journal of Mathematics and Mechanics*, *53*, 83–94. doi: 10.17223/19988621/53/8 (in Russian).

8. Gutiérrez-Vargas, G., Ruiz, A., Kim, J.-Y., & Jacobs, L. J. (2018). Characterization of thermal embrittlement in 2507 super duplex stainless steel using nonlinear acoustic effects. *NDT and E International 94*, 101–108. doi: 10.1016/j.ndteint.2017.12.004

9. Wang, W., Xu, C., Zhang, Y., Zhou, Y., Meng, S., & Deng, Y. (2018). An improved ultrasonic method for plane stress measurement using critically refracted longitudinal waves. *NDT and E International 99*, 117–122. doi: 10.1016/j.ndteint.2018.07.006

10. Smirnov, A. N., Knyazkov, V. L., Abakov, N. V., Ozhiganov, E. A., Koneva, N. A., & Popova, N. A. (2018). Acoustic evaluation of the stress-strained state of welded carbon steel joints after different modes of heat input. *Russian Journal of Nondestructive Testing*, *54*(1), 37–43. doi: 10.1134/S1061830918010072

11. Muravev, V. V., & Tapkov, K. A. (2017). Evaluation of strain-stress state of the rails in the production. *Devices and Methods of Measurements, 8*(3), 263–270. doi: 10.21122/2220-9506-2017-8-3-263-270

12. Murav'ev, V. V., Volkova, L. V., Platunov, A. V., Buldakova, I. V., & Gushchina, L. V. (2018). Investigations of the structural and strain-stress state of the rails of current production by the acoustic elasticity method. *Bulletin of Kalashnikov ISTU*, *21*(2), 13–23. doi: 10.22213/2413-1172-2018-2-13-23 (in Russian).

13. Muravev, V. V., Volkova, L. V., Platunov, A. V., & Kulikov, V. A. (2016). An electromagnetic-acoustic method for studying stress-strain states of rails. *Russian Journal of Nondestructive Testing*, *52*(7), 370–376. doi: 10.1134/S1061830916070044

14. Gonchar, A. V., Mishakin, V. V., Klyushnikov, V. A., & Kurashkin, K. V. (2017). Variation of elastic characteristics of metastable austenite steel under cycling straining. Technical Physics. *The Russian Journal of Applied Physics*, *62*(4), 537–541. doi: 10.1134/S1063784217040089

15. Mishakin, V. V., Klyushnikov, V. A., & Gonchar, A. V. (2015). Relation between the deformation energy and the Poisson ratio during cyclic loading of austenitic steel. *Technical Physics. The Russian Journal of Applied Physics*, *60*(5), 665–668. doi: 10.1134/S1063784215050163

16. Babkin, S. E. (2015). The determination of the Poisson ratio for ferromagnetic materials using the EMA method. *Russian Journal of Nondestructive Testing*, *51*(5), 303–307. doi: 10.1134/S1061830915050022

17. Murav'ev, V. V., Murav'eva, O. V., & Volkova, L. V. (2016). Influence of the mechanical anisotropy of thin steel sheets on the parameters of Lamb waves. *Steel in Translation*, *46*(10), 752–756. doi: 10.3103/S0967091216100077

18. Murav'eva, O. V., & Murav'ev, V. V. (2016). Methodological peculiarities of using SH- and Lamb waves when assessing the anisotropy of properties of flats. *Russian Journal of Nondestructive Testing*, *52*(7), 363–369. doi: 10.1134/S1061830916070056

19. Volkova, L. V., Murav'eva, O. V., Murav'ev, V. V., & Buldakova, I. V. (2019). Device and methods for measuring of acoustic anisotropy and the residual stress in the main gas pipelines metal. *Devices and Methods of Measurements*, *10*(1), 42–52. doi: 10.1134/S1061830916070056

20. Tapkov, K.A. (2018). Strain stress modeling of differential hardening rails. *Intelligent Systems in Manufacturing 16*(2), 78–83 (in Russian). doi: 10.22213/2410-9304-2018-2-78-83

21. Muravev, V. V., Volkova, L. V., Platunov, A. V., Buldakova, I. V., & Gushchina, L. V. (2018). Investigations of the structural and strain-stress state of the rails of current production by the acoustic elasticity method. *Bulletin of Kalashnikov ISTU 21*(2), 13–23 (in Russian). doi: 10.22213/2413-1172-2018-2-13-23

22. Murav'eva, O. V., & Zorin, V. A. (2017). The multiple shadow method applied to testing cylindrical objects with Rayleigh waves. *Russian Journal of Nondestructive Testing*, *53*(5), 337–342. doi: 10.1134/S1061830917050059

23. Murav'ev, V. V., Murav'eva, O. V., & Petrov, K. V. (2017). Connection between the properties of 40KH-steel bar stock and the speed of bulk and rayleigh waves. *Russian Journal of Nondestructive Testing*, *53*(8), 560–567. doi: 10.1134/S1061830917080046

24. Muravev V. V., Zlobin D. V., & Platunov A. V. (2017). Device for studies on acoustic-elastic characteristics of thin wires. *Journal of Instrument Engineering*, *60*(6), 572–577. doi: 10.17586/0021-3454-2017-60-6-572-577.

25. Strizhak, V. A., Khasanov, R. R., & Pryakhin, A. V. (2018). Features of excitation of an electromagnetic acoustic transducer under a waveguide method of testing. *Bulletin of Kalashnikov ISTU 21*(2), 159–166 (in Russian). doi: 10.22213/2413-1172-2018-2-159-166

26. Petrov, K. V., & Murav'eva, O. V. Russian Federation Patent for useful model No. 179018 (April 25, 2018).

27. Strizhak, V. A., Pryakhin, A. V., Hasanov R. R., & Efremov, A. B. (2017). Hardware-software complex for rods control by mirror-shadow method using multiple reflections. *Izvestiya vysshikh uchebnykh zavedeniy. Priborostroenie 60*(6), 565–571 (in Russian). doi: 10.17586/0021-3454-2017-60-6-565-571