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CONTACTLESS ELECTROMAGNETIC ACOUSTIC TECHNIQUES OF DIAGNOSTICS AND ASSESSMENT OF MECHANICAL PROPERTIES OF STEEL ROLLED BARS

V.V. Murav'ev[1,2*], O.V. Murav'eva[1,2], K.V. Petrov[1]

[1]Kalashnikov Izhevsk State Technical University, 7 Studencheskaya Str., Izhevsk, 426069, Russia

[2]Udmurt Scientific Center of Ural Branch of Russian Academy of Sciences, 34 T. Baramzinoy Str., Izhevsk, Russia 426067

*e-mail: vmuraviev@mail.ru

Abstract. The acoustic technologies of the mechanical properties assessment and diagnostics of steel rolled bars based on using contactless electromagnetic acoustic (EMA) transducers of longitudinal, shear and Rayleigh waves and a mirror-shadow technique on multiple reflections are presented. Dependencies of the structural sensitive acoustic factors (absolute values of longitudinal, shear and Rayleigh wave velocities, their changes during the mechanical loading, acoustoelastic coefficients, efficiency of EMA transformation) on elastic and mechanical properties, the quality of heat treatment, the structural and stress-strain state of steel bar samples from springing, low-alloyed perlite and chrome-nickel steels are investigated.

Keywords: electromagnetic-acoustic technique; velocities of elastic waves; structure; mechanical properties; stress-strain state; acoustoelasticity; defects.

1. Introduction

A wide arsenal of nondestructive physical magnetic and acoustic techniques and instruments are used to solve the problems of determining the structure, the anisotropy, the elastic and strength properties of constructional materials [1–8]. Electromagnetic acoustic (EMA) techniques of non-destructive testing are the progressive ones among modern trends of methods and means of predicting of the structure [9–14]. Contactless EMA method of excitation-receipt does not require application of the contact liquid, thus giving the possibility to perform control procedures for rough and contaminated surfaces of objects, at high and low temperatures and for objects moving at high speeds. It is important that EMA transducers allow for generating different types of waves with various polarization which in turn increases the number of informative parameters sensitive to the structure and discontinuity flaws of the metal [10].

To perform the structural analysis and flaw detection of steel rolled bars, the authors developed the technique of the mirror-shadow method on multiple reflections [15] with application of specialized transmission-type EMA transducers for radiation-receipt of shear and longitudinal radial waves [14] and surface EMA transducers for radiation-receipt of Rayleigh waves along the bar perimeter [13].

The paper presents the results of applying the developed technique for flaw detection and assessment of mechanical properties of steel rolled bars made of springing and structural steels.

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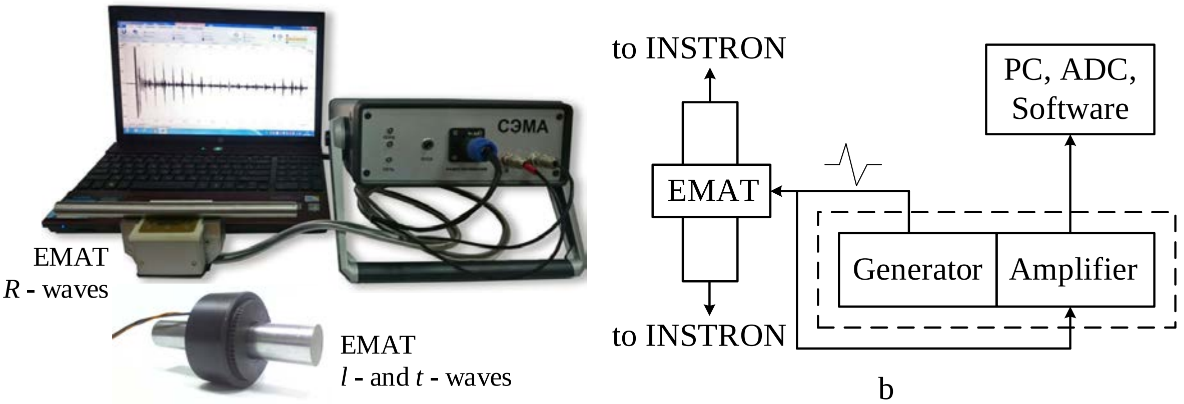
2. Applied approaches and methods

In order to assess the influence of the structure, mechanical properties and discontinuity flaws on the measured characteristics of acoustic waves, we used rolled bar samples made of structural springing steels UNS G95620 and UNS G10600 (such rolled bars are applied when producing the railway springs) and rolled bar samples made of structural low-alloy perlite steels UNS G51400, UNS G41180 and UNS G41400, and chrome-nickel steels UNS S20910 applied when producing the responsible parts of oil mining equipment: bar blanks of pump rods and shafts of centrifugal pumps. In order to assess the influence of the structural state and mechanical characteristics, the samples have been investigated on delivery and during operations of the manufacturing cycle at the stage of heat treatment for martensite, sorbite and perlite structures. To assess the sensitivity of the developed method to flaws, the following samples have been subjected to production tests at "SPC "Pruzhina", Ltd: bars made of steel UNS G95620 having diameters from 10 to 30 mm with different types of flaws – both surface and internal.

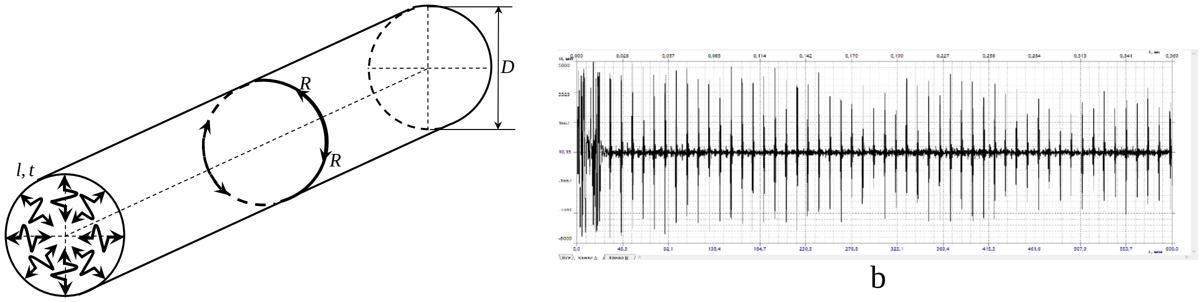
Figure 1a shows the photo of the experimental stand used at investigations [16]. In order to investigate the influence of the stress-strain state on acoustic properties, the samples have been subjected to tension at the machine Instron 300DX in the direction of the longitudinal axis (Fig. 1b). Schemes of acoustic wave propagation and specific oscillograms for a series of multiple reflections of the shear wave along the bar diameter are shown in Fig. 2.



a

b

Fig. 1. Experimental stand for structural analysis and flaw detection of bars with transmission-type and surface EMA-transducers (a), and the scheme of mechanical loading of samples (b).



a

b

Fig. 2. Scheme of propagation of longitudinal *l* and shear *t* radial waves along the section and Rayleigh *R* waves along the bar enveloping line (a), specific oscillograms for a series of multiple reflections of the shear wave along the bar diameter (b).

Velocities of propagation of longitudinal C_l, shear C_t and Rayleigh C_R waves are calculated in accordance with formulas:

$$C_{t,l} = \frac{D \cdot n}{t_n}, \; C_R = \frac{\pi D \cdot n}{t_n}, \qquad (1)$$

where D is the bar diameter, t_n is the time of the n-th reflection of the pulse in the oscillogram.

High frequency of discretization of analog-digital conversion, possibility of obtaining a series of multiple reflections and the consequent interpolation provide high accuracy of determining the velocity (0.5 m/s or 0.01%). When assessing the elastic modules of bars (Young modulus E, shear modulus G, Poisson's factor ν), their functional relation with velocities of propagation of volume (longitudinal and shear) and Rayleigh waves in the object at the known density ρ is used.

Equations of acoustic elasticity for the considered loading scheme and polarization of the applied acoustic waves are described by formulas:

$$\Delta C_l / C_{l0} = \beta^C_{zr}\sigma_{zz}, \; \Delta C_t / C_{t0} = \beta^C_{zz}\sigma_{zz}, \; \Delta C_R / C_{R0} = \beta^C_{z\varphi}\sigma_{zz}, \qquad (2)$$

where β_{ij} are acoustic elastic coefficients of velocity determined by Lame elasticity constants of the second order λ, μ and Murnaghan elasticity constants of the third order l, m, n.

3. Discussion of investigation results

Histograms of relative velocities of elastic waves for samples of steel UNS G51400 ranges in ascended order are shown in Fig. 3. The propagation velocity for longitudinal, shear and Rayleigh waves has low value in the structure of martensite obtained by hardening with the maximum degree of distortions of the crystal lattice. The consequent tempering, martempering and especially softening treatment like normalization, lead to increasing the velocity of ultrasound waves. Note, that for the most balanced hypopearlitic structures the velocities of volume and Rayleigh waves take the maximum value. At the same time, in structures of fine grain sorbite the velocity of volume and Rayleigh waves take the intermediate value between structures of martensite and the hypopearlitic mixture.

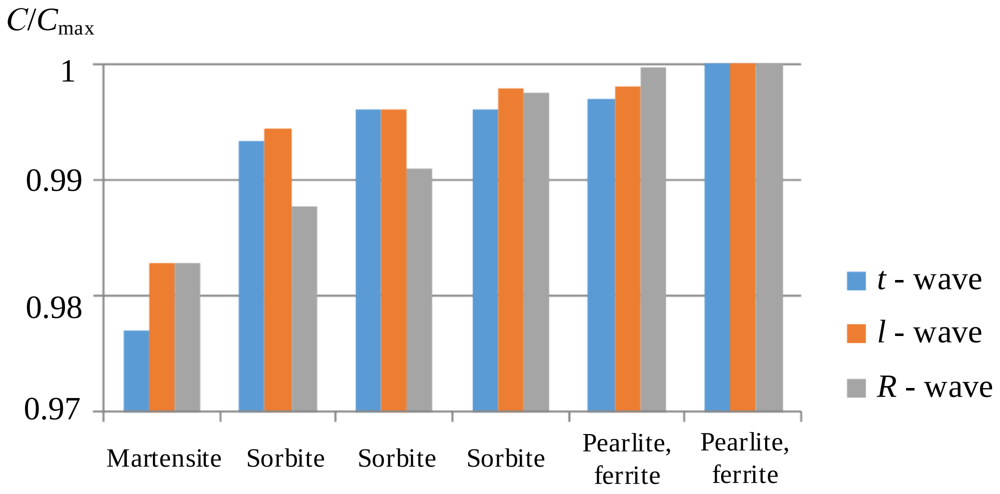


Fig. 3. Relative velocities of shear, longitudinal and Rayleigh waves vs. the structure of steel UNS G51400 samples.

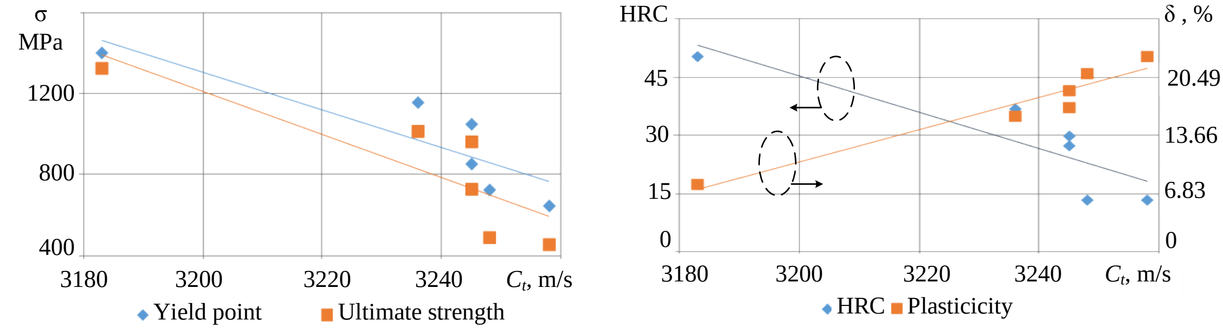


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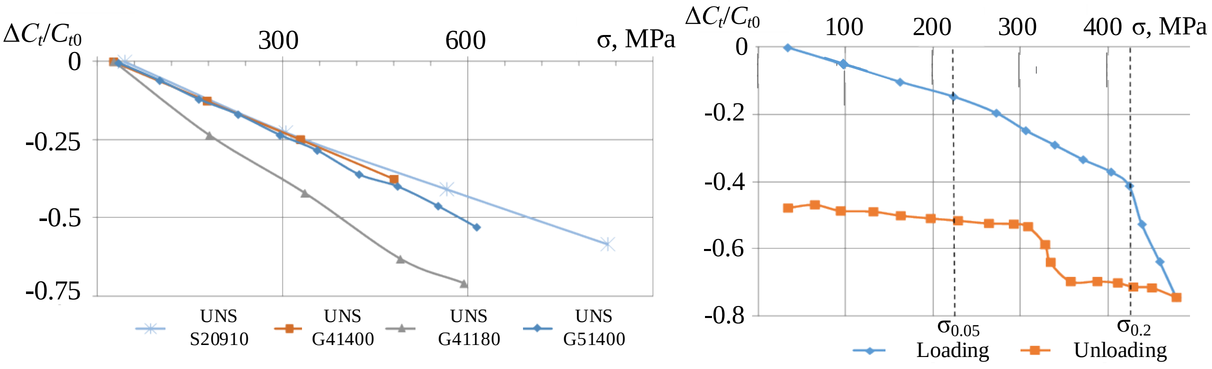
Fig. 4. Correlation of the velocity of shear waves with mechanical properties of steel UNS G51400 samples.

Here, mechanical properties (hardness, Yield point and ultimate strength, relative elongation) correspond to the structural state of samples and correlate properly with velocities of propagation of shear, longitudinal and Rayleigh waves (Fig. 4). The velocity of waves decreases with the growth of the Yield point and ultimate strength; and it increases with the growth of plasticity and relative elongation.

When the tensile load is increased, one can observe the linear decrease of the velocity of propagation of shear, longitudinal and Rayleigh waves in the elastic area for the considered grades of steel (Fig. 5a). The sensitivity of shear waves to mechanical stresses is maximum due to coincidence of their axial polarization with the direction of the applied load. As for longitudinal and Rayleigh waves with elliptical polarization, the sensitivity to mechanical stresses is considerably lower.



a b

Fig. 5. Velocity of shear waves vs. the applied tensile load for steel UNS G51400 in the elastic area (a), for steel UNS G10600 in the elastic and plastic area at loading and unloading modes (b).

In order to investigate the effect of acoustoelasticity in areas of proportionality and plasticity, steel UNS G10600 samples were subjected to high temperature annealing (820ºC, 30 minutes, cooling down in the furnace) to decrease the Yield point. Fig. 5b shows the results of variation of velocities of elastic waves in steel UNS G10600 in the elastic and plastic areas at loading and unloading of the sample. Non-linearity in the character of the curve line is observed when transiting to the elasticity area (up to 220 MPa) and farther to the Yield area (420 MPa), the coefficients of acoustoelasticity being increased here. The values of acoustoelastic coefficients of the investigated steel grades are given in Table 1.

Table 1. Acoustic elastic coefficients for velocity β_{xx}^{C} , 1/TPa.

UNS S20910	UNS G41400	UNS G41180	UNS G51400	UNS G10600		
				in elastic area	in proportionality area	in plastic area
-4.7	-5.5	-8.8	-8.2	-6.5	-14.5	-55.3

Materials and structures of the investigated samples are of essential influence on the efficiency of EMA transformation which is the additional informative parameter at structural analysis.

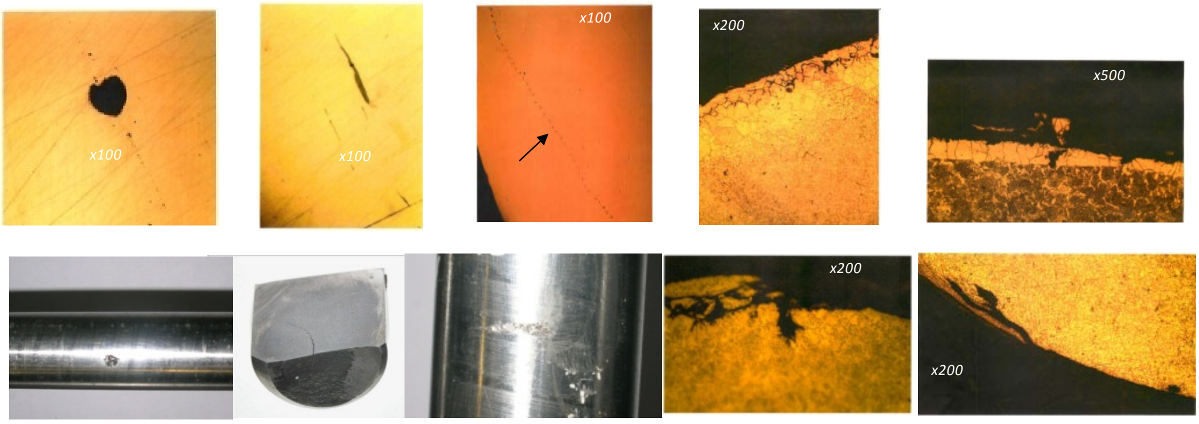


Fig. 6. Revealed defects of the rolled bars: non-metallic inclusions, folds, decarbirized layer, rolled blisters, hollows.

The developed EMA techniques are applied for flaw detection of bar stocks having diameters from 10 to 30 mm with various quality of surface treatment, made by different manufacturers, used for production of extra heavy pump rods, springs, parts of special-purpose machinery at mechanical engineering enterprises. Fig. 6 presents the photos of micro slices for certain types of the revealed defects.

It should be noted that the depth and opening of cracks, dimensions of inclusions comprise tenths of the length of the acoustic wave, whereas the traditional echo-method of ultrasound control allows for revealing the defects comparable with the wave length.

4. Conclusions

Therefore, the developed contactless EMA technique is the fine tool for assessing the elastic properties, quality of heat treatment, structural and stress strain state of rolled bars. The performed investigations revealed the possibility of its applying for the structural analysis and assessment of the stress strain state of steel bars for the following structure-sensitive factors: absolute values of velocities of longitudinal, shear and Rayleigh waves, their variation in the process of the mechanical loading, corresponding acoustic elastic coefficients vs. the velocity; and the relative variation of the amplitude under the loading process that characterizes the efficiency of EMA transformation.

Due to tuning out the acoustic contact quality and the possibility of obtaining a series of multiple reflections, the high accuracy, repeatability and validity of methods for acoustic structural analysis and flaw detection are provided.

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References

[1] E.S. Gorkunov, E.I. Yakushenko, S.M. Zadvorkin, A.N. Mushnikov // *The Physics of Metals and Metallography* **116** (2015) 147.

[2] V.N. Kostin, O.N. Vasilenko, D.Y. Filatenkov, Yu.A. Chekasina, E.D. Serbin // *Russian Journal of Nondestructive Testing* **51** (2015) 624.

[3] M.B. Rigmant, M.K. Korkh, D.I. Davydov, D.A. Shishkin, Yu.V. Korkh, A.P. Nichipuruk, N.V. Kazantseva // *Russian Journal of Nondestructive Testing* **51** (2015) 680.

[4] Y. Ivanova, T. Partalin, D. Pashkuleva // *Russian Journal of Nondestructive Testing* **53** (2017) 39.

[5] B. Wang, X. Wang, L. Hua, J. Li, Q. Xiang // *Ultrasonics* **76** (2017) 208.

[6] A.N. Smirnov, N.V. Ababkov, E.V. Kozlov, N.A. Koneva, N.V. Bykova // *Steel in Translation* **44** (2014) 742.

[7] S.A. Barannikova, A.V. Bochkareva, A.G. Lunev, G.V. Shlyakhova, L.B. Zuev // *Steel in Translation* **46** (2016) 552.

[8] A.N. Smirnov, N.V. Ababkov, V.V. Murav'ev, S.V. Fol'mer // *Russian Journal of Nondestructive Testing* **51** (2015) 94.

[9] B. Hutchinson, P. Lundin, E. Lindh-Ulmgren, D. Lévesque // *Ultrasonics* **69** (2016) 268.

[10] M. Hirao, H.Ogi, *EMATS for science and industry: noncontacting ultrasonic measurements* (Kluwer Academic Publishers, Boston, 2003).

[11] O.V. Murav'eva, M.Yu. Sokov // *Bulletin of Kalashnikov ISTU* **19(3)** (2016) 46.

[12] V.V. Murav'ev, O.V. Murav'eva, V.A. Strizhak, A.V. Pryakhin, E.N. Fokeeva // *Russian Journal of Nondestructive Testing* **50** (2014) 435.

[13] O.V. Murav'eva, V.A. Zorin // *Russian Journal of Nondestructive Testing* **53** (2017) 337.

[14] V.V. Murav'ev, O.V. Murav'eva, K.V. Petrov // *Russian Journal of Nondestructive Testing* **53** (2017) 560.

[15] O.V. Murav'eva, V.V. Murav'ev, M.A. Gabbasova, I.V. Buldakova, M.Y. Sokov // *Optoelectronics, Instrumentation and Data Processing* **52** (2016) 367.

[16] V.A.Strizhak, A.V. Pryakhin, S.A. Obukhov, A.B. Efremov // *Intellekt. Sist. Proizv.* **1** (2011) 243.