DOI 10.1007/s11003-020-00434-w
Materials Science, Vol. 56, No. 3, November, 2020 (Ukrainian Original Vol. 56, No. 3, May–June, 2020)

RELATIONSHIP BETWEEN THE PARAMETERS OF ACOUSTIC STRUCTURAL NOISE AND THE MECHANICAL PROPERTIES OF STRUCTURAL STEELS

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UDC 620.179.18

We perform the comparative analysis of the parameters of acoustic structural noise in specimens of 40G structural steel with the use of ultrasonic flaw detectors with phased arrays. It is shown that the parameter of integral density of B-scan images most completely reproduces the variations of energy of acoustic vibrations reflected from the microstructural inhomogeneities (grain-size inhomogeneity, changes in the ratios of the phase components). The relationship between the parameter of integral density of the image of acoustic structural noise R_o and the mechanical properties of 40G steel is established. We propose an improvement of the well-known method of determination of the yield limit σ_y of steels according to the results of measurements of the HB hardness. To do this, we added the parameter R_o to the equation used for computations. As a result, we deduced a new equation of the form $\sigma_y = f(R_o, HB)$ for the yield strength of 40G steel within the specified range of its values.

Keywords: degradation of properties, nondestructive testing, acoustic images of structural noise, yield limit, hardness, technical state of the metal.

Introduction

In order to guarantee the possibility of long-term operation under the conditions of high levels of wear of machines, equipment, and structures in various branches of industry, it is necessary to improve the methods used for the evaluation of their actual technical state, as well as the systems for maintenance and repair. In view of the existing large time intervals between the tests and repairs, the appearance of defects in the equipment cannot be detected in the early stage. The presence of mechanical defects, action of corrosive media and high loads of various origins, violation of the operating conditions, and insufficient amount of monitoring and diagnostic inspections serve as the main causes of the appearance of the corrosion abrasive wear and fatigue fracture [1].

The procedure of technical diagnostics of various kinds of the industrial equipment in the process of operation makes, generally speaking, possible to detect and monitor the development of crack-like defects caused by the in-service factors. However, in the process of operation, well before the appearance and development of these defects, certain local structural transformations take place in the bulk of the metal, which leads to changes in the space distribution of its physicomechanical characteristics. The degradation of the properties of materials is connected with the accumulation of microdefects. Their coalescence leads to the formation of macrodefects and the loss of the initial characteristics of the metal [2, 3]. As one of the ways to improve the informativity of evaluation of the actual technical and limiting states of structural elements with regard for the microstructure, especially in the course of their operation, we can mention the method of acoustic microscopy. It is based on the fact

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Translated from Fizyko-Khimichna Mekhanika Materialiv, Vol. 56, No. 3, pp. 44–50, May–June, 2020. Original article submitted May 22, 2019.

1068-820X/20/5603–0333

that the decrease in the velocity in polycrystalline media and in alloys with elastic anisotropy depends on the scattering of acoustic energy by metal grains. In separate crystals, it is different and depends on the direction of propagation of ultrasound relative to the symmetry axes. Therefore, in the case where ultrasound waves pass from one crystal to another and have different orientations, this quantity may undergo significant changes. As a result, we observe partial reflections, refraction of ultrasound, and transformations of the types of waves. The waves are gradually scattered in all directions. In this case, the intensity of scattering is determined by the ratio of the length of elastic waves λ to the mean diameter of grains in the crystal $\bar{d}$ and by the anisotropy of the metal. If $\lambda \le \bar{d}$, then the waves are absorbed in each grain, as in the case of a single large crystal, and their decay is mainly governed by absorption [4].

In what follows, we make an attempt to find new informative parameters of acoustic structural noise with the help of promising acoustic coherent methods. The contemporary ultrasonic flaw detectors realize the technology of ultrasonic phased arrays and make it possible to obtain the results of sonic testing of objects in the form of two-dimensional images of their internal structure, which extends the possibilities of the analysis of data.

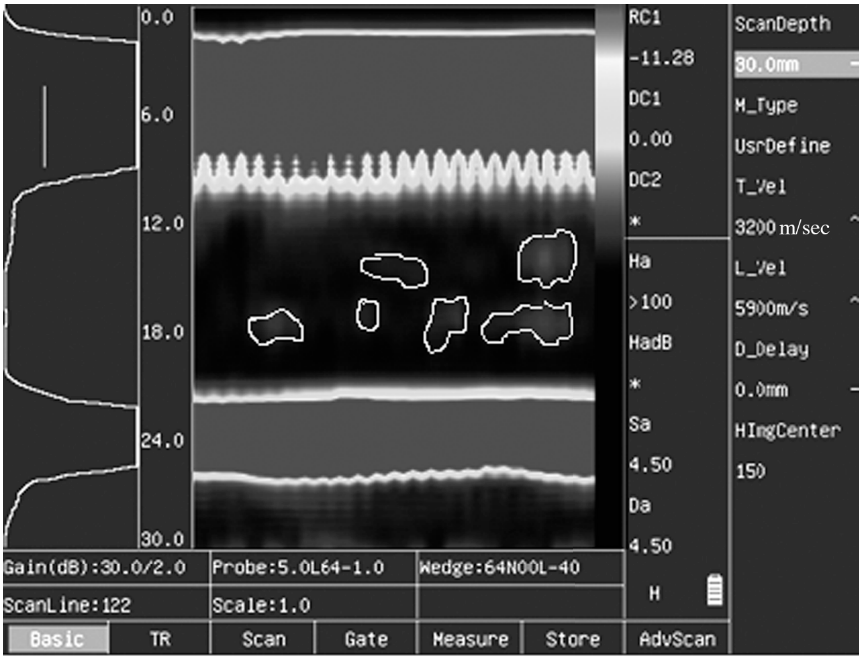
Methods of Investigation

The aim of the tests is to determine and substantiate new parameters of acoustic structural noise in steel specimens. To do this, we use plane specimens made of 40G steel $400 \times 300 \text{ mm}^2$ in cross-sectional sizes and 18.7 mm in thickness cut out from the degraded structure. This type of steel is extensively used for the production of equipment with high characteristics of strength [5], such as pipelines and vessels operating under the conditions of high pressure. The mechanical properties of these objects undergo significant changes in the course of operation. We performed our investigations in two stages [6].

In the first stage, the specimens were scanned in a SIUI CTS-602 flaw detector equipped with a 5.0L-64-1.0-10 transducer and a 64N00L-40 transient prism. As a result, we obtained a sectorial sweep of the scanned region in the screen of the flaw detector, where the amplitudes of echo-signals coming from the reflector were encoded by colors. The variations of color from dark-blue to red correspond to an increase in the amplitude of echo-pulses. As a result of refraction and transformation of ultrasonic signals from the groups of grains, the amplitudes of echo-pulses increase, which is observed at the sites of structural inhomogeneities in the form of light-blue spots in the image displayed in the screen of the flaw detector. At the sites where the values of echo-pulses are maximum, we observe the appearance of red spots. They serve as indications of the presence of defects (Fig. 1). The intensities of the brightness and color in those zones are proportional to the amplitudes of reflected acoustic waves.

The possibility of representation of the results of sonic tests in the form of two-dimensional color images of the internal structures of specimens significantly facilitates their analysis and processing. Indeed, it becomes possible to visually localize the zone of the metal with the largest number of microstructural inhomogeneities.

In the first stage of analysis of the images, we used the actual total area S of the sections of inhomogeneities in the image, i.e., the actual area of “light spots,” as a quantitative indicator of structural noise. Note that the images also contain blocks of data about the parameters of ultrasonic waves, the characteristics of adjustment of the device, the zone of delay of signals by the transient prism, and the number of reflections of the ultrasonic signals. Thus, for the subsequent analysis, the images were transmitted through the means of communication into a personal computer, where the redundant sections were removed with the help of a special software in order to select solely the sections corresponding to the so-called first reflection of the ultrasonic waves. In order to determine the total area of microstructural inhomogeneities in the image, we used a special ImageJ software.



RC1 -11.28
DC1 0.00
DC2 *
Ha >100
HadB *
Sa 4.50
Da 4.50

ScanDepth 30.0mm
M_Type UsrDefine
T_Vel 3200 m/sec
L_Vel 5900m/s
D_Delay 0.0mm
HImgCenter 150

Gain(dB):30.0/2.0
Probe:5.0L64-1.0
Wedge:64N00L-40
ScanLine:122
Scale:1.0

Fig. 1. Acoustic image of structural inhomogeneities in the screen of an SIUI CTS-602 ultrasonic flaw detector.

This software individually establishes the level of sensitivity of measuring of the parameters of the image, i.e., the operator "manually" separates the boundaries of the zone of inhomogeneities and specifies the level of contrast of the images [7]. Since the difference between color tints in the zones of microstructural inhomogeneities in the metal is insignificant against the general background of the image after binarization, the proposed method of determination of the total area of the zones of inhomogeneities is fairly labor-consuming and depends on the skills and actions of the operator.

In view of the shortcomings of the indicated procedure, for the subsequent analysis of microstructural inhomogeneities in the image, it is proposed to use the integral density of sections in the image of acoustic structural noise R_o, i.e., the amplitude (energy) of acoustic waves reflected from the inhomogeneities. To find this amplitude, we processed the images from the flaw detector in the *MatLab Image Processing Toolbox* software environment. As a result, the obtained graphic images were converted into a number matrix every element of which (number) specified the color gradient of the corresponding pixel in the image. In other words, we associated each pixel with a number specifying the color of the image. The integral density of the image is characterized by the sum of these numbers and is a dimensionless quantity.

In the second stage, we prepared 18 standard cylindrical specimens cut out from certain zones of a plane specimen of 40G steel and tested for uniaxial tension according to GOST 1497-84. The hardness of the specimens was measured with the help of a TKR-35 portable contact-resonance device. Note that the zones used to cutout the specimens were chosen with regard for the results of sonic tests carried out in the first stage of the tests.

The data of mechanical tests were used to plot the individual tensile stress–strain diagrams for each specimen. By using these diagrams, we determined the actual values of the mechanical characteristics for various sections of the plane specimen, namely, the ultimate strength, yield limit, and the characteristics of plasticity. To the database of the results of measurements of the mechanical characteristics, we also added the measured values of hardness.

Table 1
Summary Results of the Experimental Investigations

No. of specimen	Yield limit σ_y, MPa	HB	Total area of structural inhomogeneities S, px	Integral density of the image of acoustic structural noise $R_o \cdot 10^5$
1	440	221	5220	8.43853
2	400	226	7407	15.15736
3	415	223	6963	12.69751
4	425	226	152	11.73415
5	435	224	207	11.58939
6	485	226	6404	7.69845
7	420	225	9965	13.86568
8	425	218	6719	11.06315
9	435	217	5038	11.57082
10	465	230	8724	7.87664
11	380	212	209	14.81317
12	455	223	5044	9.68726
13	435	225	15124	11.59324
14	405	215	10536	15.15478
15	420	225	9853	14.17472
16	430	218	6842	11.89456
17	420	222	7952	12.14123
18	410	215	7154	12.96452

Processing and Analysis of the Results

The results of evaluation of the analyzed informative parameters are presented in Table 1. To establish the relationships between the informative parameters of the images of acoustic structural noise in the analyzed steel and its physicomechanical characteristics, we used the methods of mathematical analysis and, in particular, the graphical and correlation analyses.

The correlation relations between the investigated parameters of acoustic structural noise N and the corresponding mechanical characteristics M are determined according to the results of their binary correlation analysis [8]:

$$R(N,M) = \frac{\left[\sum_{i=1}^{n}(N_i - \bar{N})(M_i - \bar{M})\right]}{(n-1)\sigma_N \sigma_M}, \tag{1}$$

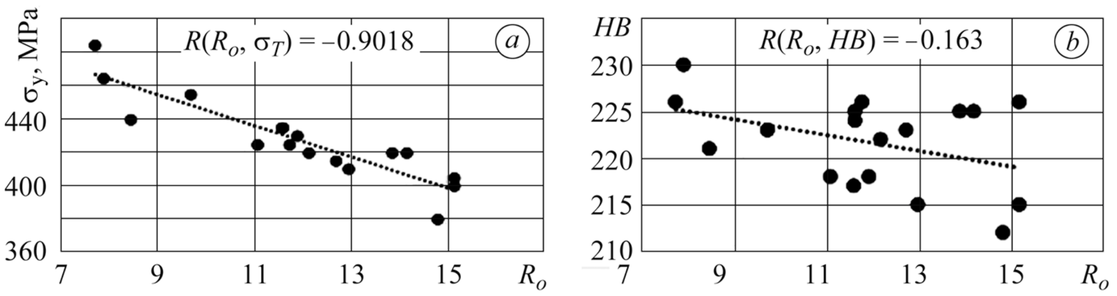


Fig. 2. Dependence of the yield limit (a) and hardness (b) on the integral density of the images of acoustic structural noise.

where $R(N, M)$ is the correlation coefficient; σ_N and σ_M are the standard deviations of the corresponding quantities, and n is the number of observations of the corresponding pairs of parameters.

It was discovered that the total area of structural inhomogeneities S (regarded as parameter of acoustic structural noise) does not correlate with the yield limit σ_{y} ($R(S, \sigma_{\mathrm{y}}) = 0.0576$). Therefore, it is not used in what follows. However, we observe a good correlation between the integral density of the image of acoustic structural noise and the yield limit σ_{y} ($R(R_o, \sigma_{\mathrm{y}}) = -0.9018$). Therefore, they are used as informative characteristics of the state of the metal. The obtained high value of the correlation coefficient reveals an almost linear relationship between the yield limit and the informative parameter of the integral density of acoustic noise. Therefore, it is reasonable to introduce this parameter as an argument in the regression model for the evaluation of the yield limit. The negative value of the correlation coefficient corresponds to the inverse relationship between these parameters. This is explained by the fact that, for high values of the integral density, ultrasonic waves are reflected from a large number of inhomogeneities in the metal structure [4], which are often concentrated in the zone with the highest stresses. In fact, the integral density R_o implicitly characterizes the sum of grains sizes of steel in a given section [4, 9]. The dependences of the yield limit and hardness on the integral density of the images of acoustic structural noise are presented in Fig. 2.

The analysis of the existing approaches to the evaluation of the yield limit as a parameter whose lowering results in the most pronounced decrease in the service life of steel structures after long-term operation [6] demonstrates that the following empirical relation is most often used for the transition from hardness to the yield limit (see GOST 10006-80):

$$\sigma_{\mathrm{y}} = 0.2HB.$$

However, if we use only hardness without general reliable information about the physicomechanical properties of the material, then we get very approximate values of the yield limit. However, by using hardness together with the parameter characterizing the microstructural specific features in the bulk of the metal, it is possible to increase the reliability of the data of measurements. In the analyzed case, due to the existence of high correlation between the values of integral density and yield limit, their simultaneous application is not reasonable. However since the correlation coefficient between the integral density and hardness does not exceed -0.16 (Fig. 3), these quantities can be regarded noncorrelated and used in the model as independent arguments.

To determine the character and form of dependence of the yield limit of steel on its hardness and the integral density of the image of acoustic structural noise, we apply the regression analysis.

We construct a regression model of the form

$$\sigma_{\mathrm{y}} = f(HB, R_o)$$

and apply the *Curve Fitting Tool MatLab* software.

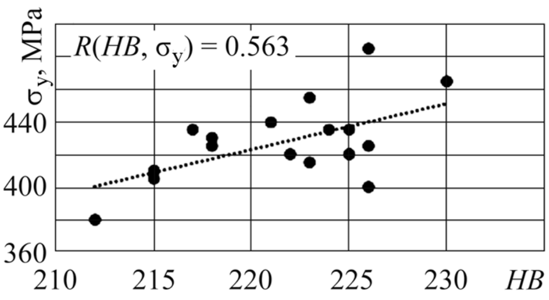


Fig. 3. Dependence of the yield limit on hardness.

The equation of linear regression for this model takes the form

$$\sigma_y = f(HB, R_o) = a_0 + a_1 \cdot HB + a_2 \cdot R_o, \tag{2}$$

where a_0, a_1, and a_2 are the regression coefficients: $a_0 = 240.7$; $a_1 = 1.381$, and $a_2 = -10.11$.

Here, the determinacy coefficient R^2 is equal to 0.8543 (the closer the values of this coefficient to 1, the better the adequacy of the model), which reflects the existence of close correlation between the analyzed parameters.

The low value of the correlation coefficient between the yield limit and hardness (Fig. 3) also reflects a nonlinear character of relationship between these parameters. Therefore, it is reasonable to construct a regression model with the nonlinear dependence on hardness. However, the number of the regression coefficients increases with the power of arguments appearing in the regression equation, which significantly complicates our calculations.

The analysis of the types of regression equations shows that the optimal results are attained if the hardness argument appears in the second power. Indeed, as the power of this argument increases further, the number of coefficients also increases but the determinacy coefficient varies insignificantly. Finally, we choose the following approximate equation:

$$\sigma_y = a_0 + a_1 \cdot HB + a_2 \cdot R_o + a_3 \cdot HB^2 + a_4 \cdot HB \cdot R_o. \tag{3}$$

Here, a_0, a_1, a_2, a_3, and a_4 are the regression coefficients: $a_0 = 13890$; $a_1 = -123.1$; $a_2 = 11.64$; $a_3 = 0.2835$, and $a_4 = -0.09933$. In this case, the determinacy coefficient of R^2 is equal to 0.8779. The root-mean square error (RMSE is the distance between two points) is equal to 9.672, whereas the residual sum of the squares is equal to 1216, which reveals a high reliability of the model. Note that the proposed model is suitable for the following measurement range of the yield limit: 380–500 MPa.

CONCLUSIONS

On the basis of the experimental data, we confirm the possibility of application of the integral density of the images of acoustic structural noise in the screen of ultrasonic flaw detectors with piezotransducers on phased arrays for the detection of changes in the microstructural heterogeneity of steels. It was established that the inverse informative parameter of the state of microstructure has a high correlation coefficient with the yield limit of 40G steel. We plotted a dependence of the form $\sigma_y = f(R_o, HB)$, which enabled one to estimate the technical states of structures made of 40G steel with the help of the improved method of determination of the yield limit of the metal according to the measured values of hardness and the integral density of the images of acoustic structural noise. The error of determination of the yield limit with the help of the constructed regression equation does not exceed 5% within the following range of values of the yield limit: 380–500 MPa.

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