Devices and Methods of Measurements
2023, vol. 14, no. 3, pp. 191–198
A.R. Baev et al.

DOI: 10.21122/2220-9506-2023-14-3-191-198

Backscattering of Ultrasonic Waves as the Basis of the Method of Control of Structure and Physico-Mechanical Properties of Cast Irons

A.R. Baev[1], N.V. Levkovich[1], E.P. Babuk[2], M.V. Asadchaya[1]

[1]*Institute of Applied Physics of the National Academy of Science of Belarus,
Akademicheskaya str., 16, Minsk 220072, Belarus*
[2]*Belarusian State University,
Nezavisimosti Ave., 4, Minsk 220030, Belarus*
[3]*Minsk Automobile Plant,
Socialist str., 2, Minsk 220021, Belarus*

Received 23.08.2023
Accepted for publication 26.09.2023

Abstract

Increasing the reliability of control of cast iron structure and its physical and mechanical characteristics is an important scientific and technical task of the machine-building industry. The paper studies the possibilities of controlling the structure of cast irons using structural noise created by ultrasonic scattering on graphite inclusions of different shapes. The subject of the present studies was such characteristics of structural noise as amplitude-temporal $A(t)$ and as root mean square value of the amplitude of the ultrasonic waves backscattering field A^N, compared with the data on ultrasonic velocity and strength or tensile strength of cast iron samples. As a result of the studies, a significant difference between the amplitude parameters of the A^N structural noise obtained for samples with different shapes of graphite inclusions at 5 MHz was revealed for the first time. So, for example, for samples of gray cast iron (Russian: СЧ10, СЧ15, СЧ20, СЧ25), having predominantly plate-like form of graphite inclusions, the value of A^N on 14–15 dB exceeds that measured in high-strength specimens of the cast iron with the prevailing form of spherical graphite inclusions ВЧ50 (Russian), etc. At the same time growth of longitudinal ultrasonic velocity amounted to 20–25 %. The method of rejection of gray cast iron from high-strength cast iron according to the data of amplitude parameters of structural noise A^N at unilateral and local sounding of the object without using an additional reference signal reflected from its oppositional wall is suggested.

Keywords: ultrasonic wave scattering, graphite inclusions of different shapes, method of controlling the structure and strength of cast irons, ultrasonic probes

Адрес для переписки:
Баев А.Р.
Институт прикладной физики НАН Беларуси,
ул. Академическая, 16, г. Минск 220072, Беларусь
e-mail: baev@iaph.bas-net.by

Address for correspondence:
Baev A.R.
Institute of Applied Physics of the National Academy of Science of Belarus,
Akademicheskaya str., 16, Minsk 220072, Belarus
e-mail: baev@iaph.bas-net.by

Для цитирования:
A.R. Baev, N.V. Levkovich, E.P. Babuk, M.V. Asadchaya.
Backscattering of Ultrasonic Waves as the Basis of the Method of Control of Structure and Physico-Mechanical Properties of Cast Irons.
Приборы и методы измерений.
2023. – Т. 14, № 3. – С. 191–198.
DOI: 10.21122/2220-9506-2023-14-3-191-198

For citation:
A.R. Baev, N.V. Levkovich, E.P. Babuk, M.V. Asadchaya.
Backscattering of Ultrasonic Waves as the Basis of the Method of Control of Structure and Physico-Mechanical Properties of Cast Irons.
Devices and Methods of Measurements.
2023, vol. 14, no. 3, pp. 191–198.
DOI: 10.21122/2220-9506-2023-14-3-191-198

DOI: 10.21122/2220-9506-2023-14-3-191-198

Обратное рассеяние ультразвуковых волн как основа метода контроля структуры и физико-механических свойств чугунов

А.Р. Баев[1], Н.В. Левкович[2], Е.П. Бабук[3], М.В. Асадчая[1]

[1]*Институт прикладной физики Национальной академии наук Беларуси,*
ул. Академическая, 16, г. Минск 220072, Беларусь

[2]*Белорусский государственный университет,*
пр-т Независимости, 4, г. Минск 220030, Беларусь

[3]*Минский автомобильный завод,*
ул. Социалистическая, 2, г. Минск 220021, Беларусь

Поступила 23.08.2023
Принята к печати 26.09.2023

Повышение надёжности контроля структуры чугунов и их физико-механических характеристик является важной научно-технической задачей машиностроительной промышленности. В работе изучены возможности контроля структуры чугунов, используя структурный шум, создаваемый рассеянием ультразвуковых колебаний на графитовых включениях разной формы. Предметом настоящих исследований являлись такие характеристики структурного шума как амплитудно-временные $A(t)$ и среднеквадратичные амплитуды A^N волн рассеяния, сопоставляемые с данными по скорости ультразвуковых колебаний, а также прочностью или временным сопротивлением на растяжение образцов чугунов. В результате исследований впервые выявлено существенное различие между амплитудными параметрами структурного шума A^N, полученными для образцов с разной формой графитовых включений на частоте 5 МГц. Так, например, для образцов серого чугуна (СЧ10, СЧ15, СЧ20, СЧ25), имеющих преимущественно пластинчатую форму графитовых включений, величина A^N на 14–15 дБ превышает ту, что измерена в высокопрочных чугунах с превалирующей формой включений графита шаровидной формы – ВЧ50. При этом, рост продольной скорости ультразвука с увеличением временного сопротивления составил ≈ 20–25 %. Предложен метод отбраковки серого чугуна от высокопрочного по данным амплитудных параметров структурного шума A^N при одностороннем и локальном прозвучивании объекта без использования дополнительного опорного сигнала, отражённого от его оппозитной стенки.

Ключевые слова: рассеяние ультразвуковых волн, включения графита разной формы, способ контроля структуры и прочности чугунов, ультразвуковые преобразователи

Адрес для переписки:
Баев А.Р.
Институт прикладной физики НАН Беларуси,
ул. Академическая, 16, г. Минск 220072, Беларусь
e-mail: baev@iaph.bas-net.by

Address for correspondence:
Baev A.R.
Institute of Applied Physics of the National Academy of Science of Belarus,
Akademicheskaya str., 16, Minsk 220072, Belarus
e-mail: baev@iaph.bas-net.by

Для цитирования:
A.R. Baev, N.V. Levkovich, E.P. Babuk, M.V. Asadchaya.
Backscattering of Ultrasonic Waves as the Basis of the Method of Control of Structure and Physico-Mechanical Properties of Cast Irons.
Приборы и методы измерений.
2023. – Т. 14, № 3. – С. 191–198.
DOI: 10.21122/2220-9506-2023-14-3-191-198

For citation:
A.R. Baev, N.V. Levkovich, E.P. Babuk, M.V. Asadchaya.
Backscattering of Ultrasonic Waves as the Basis of the Method of Control of Structure and Physico-Mechanical Properties of Cast Irons.
Devices and Methods of Measurements.
2023, vol. 14, no. 3, pp. 191–198.
DOI: 10.21122/2220-9506-2023-14-3-191-198

Introduction

Increasing the reliability of testing the structure of cast irons and their physical-mechanical properties (PMP) by nondestructive methods is an important technical and scientific problem of the machine-building industry. Significant efforts of developers of such methods and means of control are directed on attraction and use of new effects of interaction of external fields, including acoustic, electromagnetic, etc. for expansion of technical possibilities and nomenclature of controlled objects. It concerns not only the methods of nondestructive testing, which give at "volume probing" of metal averaged indicators of informative parameters correlating with the structure and PMP, which is realized as a rule by acoustic methods [1], but also obtaining such data on the properties of local areas of the object. As for a number of methods of control of structure and PMP of cast irons by electromagnetic methods, for example [1–3], their use has limitations due to high sensitivity to the mobility of domains in alternating fields. And this, in turn, depends on a number of peculiarities of the casting technology itself and proper holding of the processes running in accordance with the Technical Conditions at a particular production plant, including the additives introduced into the metal, holding of the melting temperature regime, etc.

It should be noted that in some cases sufficiently reliable information on the structure of cast irons is achieved in the evaluation of small-sized products, when it is possible to carry out volumetric magnetization of products. In this case, a number of factors that reduce the reliability of estimation of PMP and structure of the material are reduced [3]. Sometimes, under certain conditions (as a rule, laboratory), quite important information about the PMP of cast irons can be obtained by measuring the structural noise or Barkhausen noise created by the motion of the domain structure under the influence of a low-frequency magnetic field applied tangentially to the surface of a specially protected object surface [2]. However, as mentioned above, the measured output signal readings are quite sensitive to the influence of the above factors on the signal-response when the depth of local probing does not exceed 0.5–1.0 mm.

With regard to the use of ultrasonic methods of structural and PMP testing of cast irons, the magnetic characteristics of the latter practically do not affect the values of acoustic parameters, including the velocity C of a particular ultrasonic mode, attenuation and scattering coefficients on structural inhomogeneities – mainly graphite inclusions. It is very important that the shape and geometrical parameters of the latter have a significant influence on the strength properties of cast irons, as well as on the elastic Young's moduli E and shear moduli G, the coefficient of volumetric compression K_C, and the density of the material ρ. In this case:

$$C_{L,T,R} = (E/\rho)^{0.5} F_{L,T,R}\,, \quad (1)$$

where $F_{L,T,R}$ is a function depending mainly on the Poisson's ratio, and the indices L, T and R refer to the longitudinal, transverse and Rayleigh modes, respectively.

In view of the relationship between ultrasound velocity and PMP, simplicity of realization and wide possibilities of volumetric, surface, subsurface sounding of cast irons, such devices and acoustic methods find more and more widespread application for structural analysis of cast irons [4–6]. It should be noted that informative parameters having a functional relationship with the ultrasonic velocity (and, accordingly, with elastic moduli) can be used to determine the ultrasonic velocity, including, for example, critical angles of passage or reflection of elastic waves from the liquid-iron boundary, etc. [7].

In this case, naturally, as in the previous case, it is required to finish the local surface of the object to the roughness R_z < 5–10 μm, as well as to create a local or immersion bath and a device for controlling the angle of incidence (reception) of the ultrasonic beam on the object.

In some cases, the methods of sounding the object by using the signal-response, characterizing the attenuation parameters of ultrasonic waves, including the attenuation coefficient of ultrasonic or spectral characteristic of the signal $A(\omega)$ [8] are promising. However, despite a number of advantages, the use of such a method, there is a disadvantage due to the fact that its realization requires the appropriate orientation of the oppositional surface of the object in relation to the working surface of the input and mechanical processing of both surfaces at the thickness of the layer of sounded metal $h > h_0$, providing the necessary accuracy of amplitude measurements. Note that a similar problem occurs for the most widely used in practice ultrasonic control method mentioned above, which consists in determining the ultrasonic velocity well correlated with the PMP of cast irons.

In the present work we suggest to expand technical possibilities of structuroscopy for rejection of high-strength cast iron from gray cast iron, to apply the method consisting in using as an informative parameter the mean-square amplitude of waves backscattered on graphite inclusions (or structural noise). It determined in the characteristic time range $\Delta t_{21} = t_2 - t_1$, where the choice of time boundaries t_i is realized from the condition, at which the superimposition of additional waves is excluded. It is assumed that the control of the local subsurface zone of the object can be realized without using data on the parameters of the acoustic signal reflected from the opposing wall of the object under study.

It should be noted that similar problems for estimating the grain baleness or determining the boundary of the thermally hardened layer characterized by the difference in grain size of the structure of the metal hardened by chemical-thermal treatment were solved, for example, in [9–10]. In this case, as it is known [1], such acoustic samples as ultrasound velocity *C*, specific acoustic resistance *R* and elastic moduli change not so significantly depending on the baleness or grain size of the metal.

In [10]. to increase the reliability of measurements it was proposed to use as a reference signal to use the amplitude of the "penetration signal" A_S, which is a pulse of a surface wave propagating along the boundary of the ultrasonic probe (UP) with the steel surface from the ultrasonic source to the receiver of waves. The object of the present research are cast iron samples differing in the form of graphite inclusions, on which, according to known data, both physical-mechanical and acoustic properties correlating with them essentially depend. In this case, the change in the ultrasonic velocity and specific acoustic impedance can reach tens of percent. It should be expected that the scattering field of ultrasonic waves on the ensemble of graphite inclusions will change more markedly depending on their shape, size and content of the spherical, vermicular graphite, which, naturally, requires research to develop a method for rejecting cast irons according to their amplitude characteristics of structural noise.

Thus, the purpose of the present work was to study the features of ultrasonic wave scattering in cast iron samples depending on their structure, tensile strength, as well as correlated with them ultrasonic velocity, which is of interest for the development of a method of rejecting cast iron, for example, high-strength from gray cast iron.

Development of the methodology and scheme of acoustic measurements

Below, along with the development of a methodology for research into the scattering of ultrasonic waves mainly on graphite inclusions of cast irons and the analysis of the acoustic path, are the means of measurement explained in Figure 1. The latter illustrates the scheme of measurements designed to determine the amplitude characteristics of the scattering field of the probing signal, which is the subject of research.

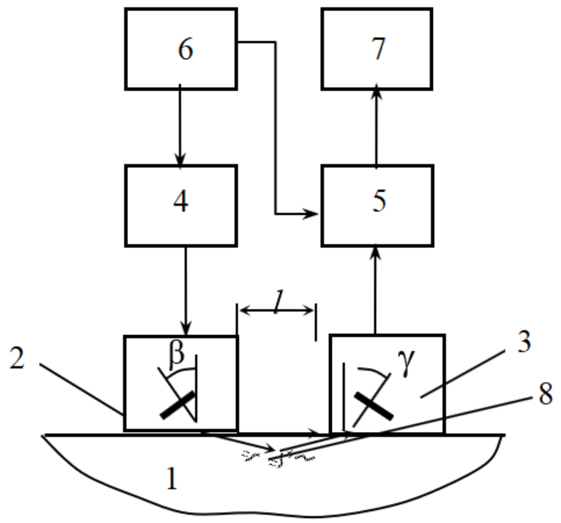

Figure 1 – Scheme of the experimental study of the influence of cast iron structure on the amplitude characteristics of the backscattering field: 1 – object; 2 and 3 – emitting and receiving elements (sensors) of the transducer; 4, 5 – generator and receiver of electrical impulses, respectively; 6 – device I1-8; 7 – electronic block of signal processing; 8 – graphite inclusions

The object of research were the samples of cast irons produced at Minsk Automobile and Tractor Plants, belonging to gray cast iron grades (СЧ10-СЧ25), high-strength (ВЧ50), ductile (КВЧ35), having ferrite and pearlite phases in the base. Primary information about the structure and their physical and mechanical properties, including tensile strength, hardness, etc., was obtained on the submitted samples.

At the preliminary stage of the work, a set of studies was carried out to select the optimal design of the device containing two prismatic UP, with characteristic prism angles ($4^0 < \{\gamma, \beta\} < 10^0$) and operating frequency f = 1.8–10 MHz. At the same time, the distance between the emitting and receiving transducer of the ultrasonic device was varied in the range l = 0–2 mm, and the angle β = γ. In view of the small angles of the UP prism, it is fair to estimate the input angle of the longitudinal ultrasonic wave into the steel according to (1):

$$\alpha = \arcsin[(C_1/C_2)\sin\beta \approx \beta\, C_1/C_2\,, \quad (2)$$

where C_1 is the ultrasonic sounding velocity in the UP sounding prism; C_2 – in cast iron, which, as will be shown below, increases with increasing number of gray cast iron grade (from СЧ10) to high-strength (ВЧ50). increases with increasing strength of samples up to 30 %. As follows from (3), in this case, the angle of entry of the ultrasonic coil into the metal should decrease by almost the same amount).

Installation for research (Figure 1) contains a generator of pulse signals with bell-shaped envelope fed to the radiating probe of the device, which excites in the sample elastic oscillations, part of the energy flow of which spreads along the interface surface of the working surface of the UP, cast iron wetted with contact fluid. The other part is scattered on graphite inclusions (predominantly) and metal grains, forming the so-called field of ultrasonic vibrations scattering on material inhomogeneities or "structural noise" caused mainly by graphite inclusions. Then the signal is received by the receiving probe amplified and gets simultaneously to the electronic signal processing unit and to the computer screen. With the help of a special program, the processing and determination of the amplitude value of the of the scattering waves or structural noise of the A^N recorded at which there is no superposition of additional parasitic signals and the arrival time of the impulse reflected from the opposing wall $t = t_2$. In this case, the A^N is defined as root mean square value of the amplitude of the ultrasonic wave scattering field measured in the time range $t_2 < t < t_1$, and:

$$A^N = [(\sum_{i=1}^{i_0}(A_i)^2]^{0.5})\,/\,i_0, \quad (3)$$

where $A_i = A(t_i)$ is the amplitude of the i^{th} signal measured at the moment t_i.

Synchronization of electronic units and selection of the working area of the receiving signal processing is performed with the help of the time interval meter И1-8 (Russian). (Its use allows to measure by echo-method the longitudinal wave velocity in cast iron with an acoustic base of 4 cm with an error not worse than 0.3–0.5 %). To increase the reliability of measurements the following is performed. At the beginning, the adjustment of the measuring system and electronic units is checked on each sample using a special witness sample. And to increase the reliability of the A^N value estimation, it is determined as the average of four readings recorded on the sample surface when the UP shifted by 0.5–1.0 mm relative to the initial position.

Research results and their discussion

As mentioned above, the subject of the present studies are acoustic parameters of surface and subsurface waves backscattered on graphite inclusions, which are compared with our data on ultrasonic velocity, as well as data on physical and mechanical properties, including tensile strength, etc., measured on the equipment of the central tensile tear strength laboratories of Minsk automobile and tractor plants.

The first, or preliminary stage of the work was to identify plant the optimal device design and ultrasonic (piezoelectric) transducer, operating frequency which is expected to be published later. It was found that the best reliability and stability of readings is achieved when the distance between the prisms of UP $l \to \Delta l$, where Δl is the thickness of the sound-insulating layer separating the emitting and receiving prisms of the ultrasonic probe, the design of which is similar to the separately combined transducer [1]. The best sensitivity of amplitude readings to changes in the structure of cast irons was observed at operating frequencies f = 4–5 MHz.

Moreover, Figure 2 shows characteristic dependences of amplitude-time characteristics $A(t)$ of the field of scattering of the acoustic signal on the graffite inclusions of different shapes, called "structural noise".

Figure 3 illustrates an important result of the work – dependence of the basic characteristic of structural noise A^N (Formula 1) obtained on cast iron samples with different shape of graphite inclusions in the selected time interval Δt_{21}, as well as the velocity of ultrasonic testing from the value of their strength or tensile tear strength σ.

As can be seen from the presented in Figure 2 amplitude-temporal characteristics of structural noise $A(t)$ quite clearly traced their growth with "complication" of the form of graphite inclusions from spherical (samples ВЧ50) to lamellar (СЧ15, СЧ25), differing in value σ. This is confirmed more clearly by the data of change in the mean-square amplitudes of A^N structural noise and ultrasonic sounding velocity from the value characterizing the strength of materials (Figure 3). In the first case this difference is of 13–14 dB, and when comparing the obtained data for samples ВЧ50 and КВЧ5 it decreases up to 7–8 dB. As for the ultrasonic velocity, its change is of 20–25 %.

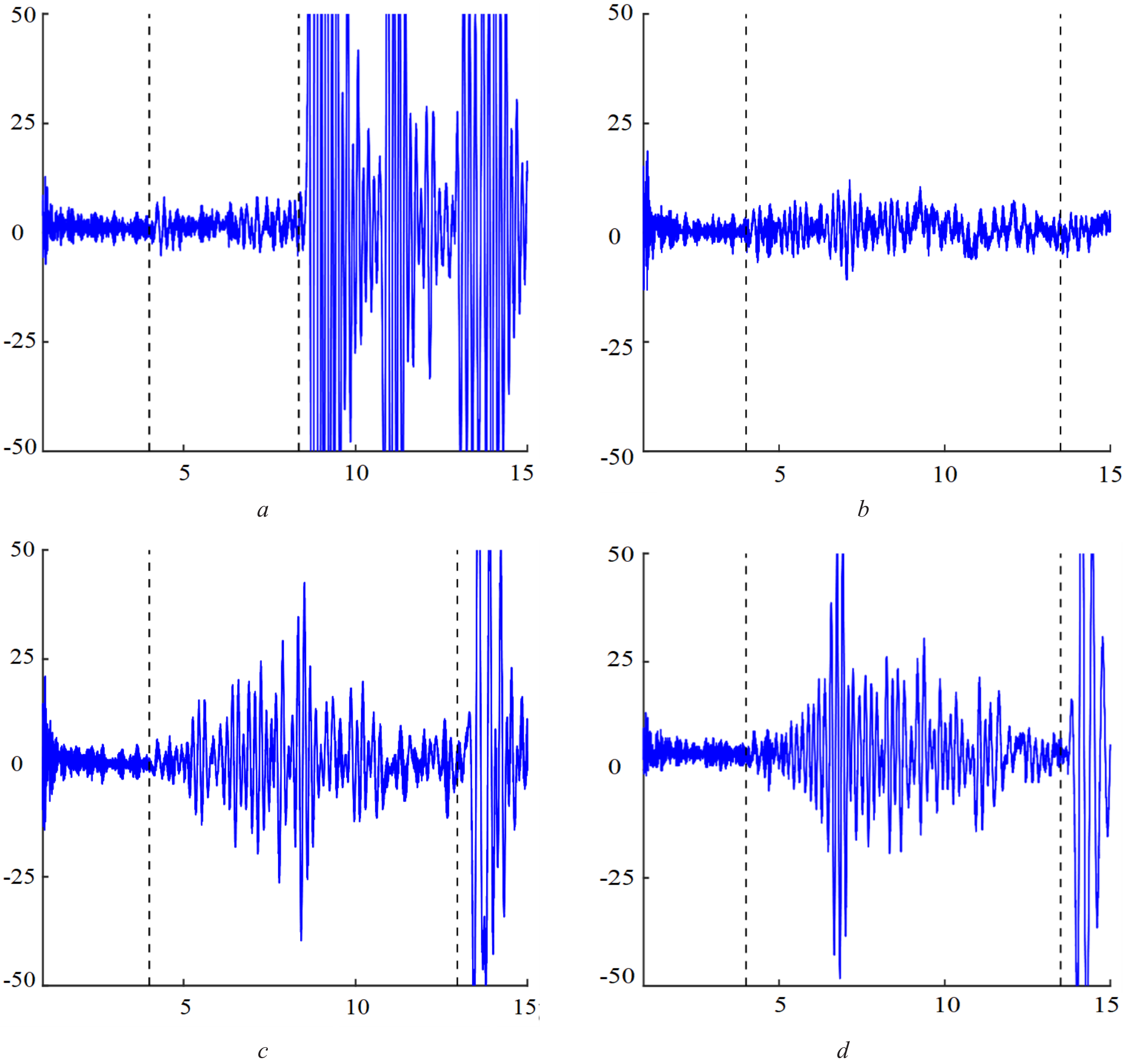

Figure 2 – Characteristic amplitude-time dependences of the structural noise caused by ultrasonic scattering on graphite inclusions in cast irons of ВЧ50 (*a*), ЧВГ35 (*b*), СЧ25 (*c*), СЧ15 (*d*): root mean square value of the amplitude of the ultrasonic waves backscattering field characterizing the structural noise A^N, mV = 2 (*a*), 3,1 (*b*), 8,8 (*c*), 12 (*d*)

On the basis of the data obtained above it should be concluded that it is possible in principle to carry out quite reliably rejection of high-strength cast irons from gray irons of the specified grades, as well as those that are close to them in properties, which is very important for expanding the technical possibilities of diagnosing the structure of cast irons and their properties. It should be noted that it is preferable to use the proposed method in those cases when:

– there are difficulties or practically impossible to apply known acoustic methods of probing, including measurement of the ultrasonic velocity, signal spectrum or attenuation coefficient, which is mainly due to the shape and geometry of the controlled object;

– additionally requires probing the structure of the material in certain local zones of the object in the absence of a reference signal created by the reflection of the acoustic pulse from the opposing.

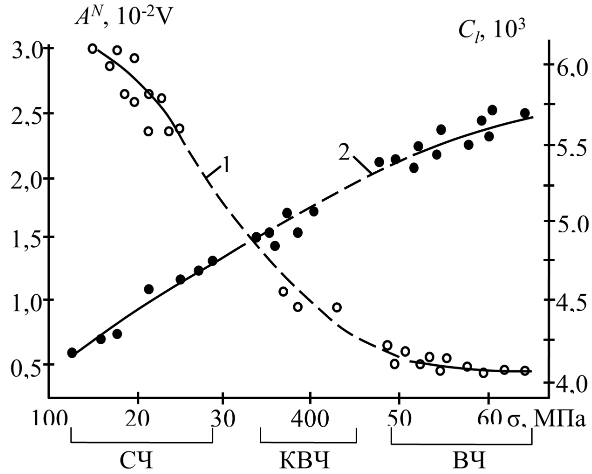

Figure 3 – Experimental dependences of the root mean square value of the amplitude of the ultrasonic waves backscattering field characterizing the structural noise (1) and longitudinal ultrasonic velocity (2) on strength or temporary tensile strength

As for the depth of metal probing h, it can be estimated on the basis of data on the above-mentioned characteristic time interval $t_2 < t < t_1$ of the fixed structural noise created by the acoustic pulse at scattering, which arises as a result of signal scattering on grafite inclusions:

$h \approx 0.5C\,(t_2 - t_1)$,

which reaches 5–10 mm. At the same time, the use of Barkhausen noise [2] for this purpose, even in the best design, gives information about the properties of cast iron to a depth of no more than 0.5–1 mm.

It should be noted that at present the theoretical description of the above processes of ultrasonic scattering on graphite inclusions having a very complex shape and representing an ensemble of spatially distributed chaotically scatterers (reflectors) is the ultrasonic wavelength, is not possible. Analyzing the influence of the shape of graphite inclusions (as well as the area of the metal-graphite boundary S) on the A^N amplitude parameters and the course of the dependence of $A(t)$ on σ, we to the roughness predominantly can state their simultaneous decrease. It is assumed that there is the increase in the area of interaction of the acoustic field with the ensemble of ultrasonic scatterers, as well as its special geometry, that have a significant effect on the mechanism of interaction of elastic oscillations with inhomogeneities of inclusions and on the intensity of structural noise received by the UP transverse dimensions $d_i << \lambda$ where λ is the ultrasonic wavelength, is practically impossible.

As it follows from our study the evaluation of cast iron structure by the proposed method depends on the requirements to the reliability of measurements, which mainly depends on the preparation of the contact surface area of the object on the area of 1–1.5 cm^2, including its roughness (R_z < 5–10 µm). For convenience of operation and constancy of acoustic contact in any spatial position of the ultrasonic device on the object, it is proposed to use compact magnetic nozzles made of rubber.

Conclusion

On the basis of the developed methodology and installation, a complex of studies of structural noise created as a result of ultrasonic waves dissipation on graphite inclusions of different shapes at one-way sounding of grey iron samples (СЧ10, СЧ15, СЧ20, СЧ25), high-strength iron (ВЧ50), forging iron (КВЧ35). At the selected optimal operating frequency of 5 MHz the amplitude-time $A(t)$ is obtained, as well as the mean-quadratic dependence of the amplitude of A^N, scharacterizing the structural noise, and longitudinal wave velocity on strength or temporary resistance to rupture at a tensile σ = 120–165 MPa.

As a result of the research, a significant difference between the parameters of structural noise A^N of the samples to study was revealed. For example, for grey cast iron samples (СЧ10–СЧ25), which have predominantly lamellar graphite inclusions, the A^N value is of 13–14 dB or more than that measured in high-strength cast iron ВЧ50 specimens with the prevailing form of spherical graphite inclusions. At the same time, it was found that ultrasonic velocity speed decreasing were to be of 20–25 % respectively. For cast iron samples КВЧ35, the measured A^N value is of 4–5 dB less than that of the prevailing form of spherical graphite samples of cast irons.

For the first time, a method for rejecting high-strength cast iron grades ВЧ with number 50 and more – from grey cast iron is proposed, consisting in for one-way ultrasound input-reception of metal without the use of an additional support signal reflected from the opposing wall, and determination of the mean quadratic amplitude root mean square value of the amplitude of the ultrasonic waves backscattering field on graphite inclusions in a specified time interval.

References

1. Ermolov IN, Lange YV. Nondestructive testing: handbook: in 8 vol. Vol. 3. Ultrasonic control. 2nd ed., revision. Moscow: Mashinostroenie. 2006. 864 p.

2. Busko VN, Vengrinovich VL, Chepyzhov BA. Non-destructive testing of cast iron products by the Barkhausen effect method. Non-destructive testing and diagnostics. 2010;(4):18-29. (In Russ.).

3. Sandomirsky SG. Peculiarities of links between the magnetic properties of cast irons with their structure and magnetic methods of control of cast iron castings (review). Casting and Metallurgy. 2016;4(85):96-10.

4. Orlowicz W, Tupaj M, Mróz M, Guzik E, Nykiel J, Zając A, Piotrowski B. Ultrasonic Assessment of Shape Index and Number of Graphite Precipitations in Spheroidal Cast Iron Manufactured in the Foundry MET-AL-ODLEW Sp. J., Archives of Foundry Engineering. 2009;9(4):179-182.

5. Baev AR, Mayorov AL, Konovalov GE. Ultrasonic inspection of objects with layered and heterogeneous structure. Science and Innovation. 2015;2(3):14-17.

6. Danilov V N, Voronkova LV. Investigation of possibilities of ultrasonic control of cast iron with lamellar graphite using standard direct transducers. Control. Diagnostics. 2020;1(23):4-12.

7. Baev AR, Asadchaya MV, Mayorov AL, Sergeeva OS, Delenkovskiy NV. Possibilities of using amplitude-angle characteristics of surface and subsurface waves for control of materials with surface hardened inhomogeneous layer. Devices and Methods of Measurements. 2022;13(4):263-275.
DOI: 10.21122/2220-9506-2022-13-4-263-275

8. Vadim N. Danilov, Liubov V. Voronkova. Attenuation of Ultrasonic Longitudinal Waves in Cast Iron with Flake Graphite on the Characteristics of Pulse Signals. Bulgarian Society for NDT International Journal "NDT Days". 2019;2(3):167-181.

9. Nowacki K. Possibility of Determining Steel Grain Size Using Ultrasonic Waves, Metalurgija. 2009; 48(2):113-115.

10. Baqeri, R., Honarvar, F., Mehdizad, R., Case Depth Profile Measurement of Hardened Components using Ultrasonic Backscattering Metod, 18th World Conference on Nondestructive Testing Proceedings, pp. 16-20. April 2012, Durban, South Africa.

11. Muravyev VV, Muravyeva OV, Dedov AI, Baiteriakov AV. Control of structural state of steels by means of acoustic noise. Devices and methods of measurements. 2014;2(9):62-64.