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MINERALOGICAL ANALYSIS OF IRON ORE USING ULTRASONIC WAVE PROPAGATION PARAMETERS

Natalia MORKUN*, Gerhard FISCHERAUER*, Vitalii TRON, Alona GAPONENKO*****

*Chair of Measurement and Control Systems, Bayreuth University, Universitätsstraße, 30, Bayreuth, Germany
**Automation, Computer Science and Technologies Department, Kryvyi Rih National University, Vitalii Matusevich St., 11, Kryvyi Rih, Ukraine
***Research Department, Kryvyi Rih National University, Vitalii Matusevich St., 11, Kryvyi Rih, Ukraine

nmorkun@gmail.com, mrt@uni-bayreuth.de, vtron@knu.edu.ua, a.haponenko@protonmail.com

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Abstract: Availability, relative simplicity and low cost, combined with ever-increasing capabilities, have led to a significant increase in the use of ultrasonic measurements of mining process variables in recent times. The scope of application varies from the study of the characteristics of raw materials and products of its processing to the operational assessment of the current parameters characterising the state of the process equipment. The purpose of this study is to develop methods for obtaining information about the characteristics of mineral raw materials as a result of ultrasonic logging of wells in a rock mass. The proposed approach makes it possible to improve the quality of information support for the management of technological processes of mining and processing of ore and thereby improve the quality of products supplied to the metallurgical stage and reduce overall production costs.

Key words: ultrasonic characteristics, scattering, estimation, mineral components

1. INTRODUCTION

Global demand for iron ores to meet the ever-growing needs of ferrous metallurgy requires the use of all available resources [1–3]. To estimate reserves of iron ore and design technological processes for its enrichment, in order to obtain a high-quality concentrate, knowledge about the mineralogical characteristics of the extracted raw materials is necessary [4, 5]. Although ultrasonic testing is non-destructive and relatively easy to implement, its potential has not yet been fully realised in rock characterisation, as the methodology and technical base strongly influence the obtained results [6–8].

At the same time, quantitative ultrasound (QUS) methods are widely used not only in technical applications but also in other branches of science and technology [9–11]. These methods make it possible to obtain estimates of attenuation, scattering and other acoustic properties of the medium under study from frequency-dependent probing signals. Specially equipped ultrasonic scanners produce ultrasonic echoes for online analysis [12]. The echo power spectra are obtained from the window segments of these signals. Echoes from a reference medium simulating certain formations are used to account for systemic data dependencies. Depth-dependent changes in the ratio of the power spectra of the studied formation to the reference medium make it possible to estimate the attenuation coefficient in the medium. Further processing gives estimates of the backscatter coefficient.

2. LITERATURE ANALYSIS

In geological and geotechnical engineering, various geomechanical parameters are widely used, such as modulus of elasticity, modulus of deformation, Poisson's ratio, uniaxial compressive strength, shear strength, tensile strength and point load index to characterise the rock mass [13, 14]. However, there are no direct methods by which these properties can be assessed in the laboratory or in the field without a time-consuming procedure. An ultrasonic method based on indirect measurements is proposed to determine these characteristics of rocks [15]. It is known that there is a correlation between compression wave velocity and geomechanical properties of sedimentary rocks such as sandstones and carbonates. However, these dependencies do not consider the change in the mineralogical composition of the rock, its porosity and texture when deriving relationships. In this study, the authors evaluate compression wave velocity variability using fragmented analysis of major mineral constituents, porosity changes and saturation conditions to classify a rock mass. The resulting template can become the basis for lithology-based interpretation of more realistic geomechanical properties and thus emphasises the importance of a comprehensive study that includes geological, petrophysical and engineering data.

In paper [16], an assessment of rock properties was given using the method of pulsed ultrasonic measurements and correlation analysis of static and dynamic elastic constants. Formation elasticity characteristics, including Young's modulus, Poisson's ratio and shear modulus, are used as input parameters to predict wellbore instability and sanding. These parameters are usually estimated from the results of laboratory experiments on core samples and are called static elastic properties. This is a costly and time-consuming approach requiring special sample preparation. An alternative laboratory approach is to measure the dynamic modulus characteristics on a core sample using the acoustic method of acoustic travel time (ATT). The authors have conducted a large number of ATT tests on various types of rocks in combination with the measurement of other physical and mechanical properties of rocks, including density, porosity, water absorption, uniaxial compressive strength and indirect tensile strength. Statistical analysis of the results made it possible to establish a correlation between the velocity of elastic waves and the physical and mechanical properties of the rock.

Several papers [17, 18] emphasise the critical importance of the physical and mechanical properties of rocks for their analysis and evaluation. Study [19] was aimed at studying some properties of quartz-mica schist (QMS). In an economical way, a correlation was established between the results of non-destructive and destructive test samples. With simple regression analysis, good correlations were obtained between ultrasonic wave velocities and QMS rock properties. The results were further improved with multiple regression analysis. They were also compared with data from other available empirical studies. General equations covering all types of rocks do not give a reliable assessment of the properties of rocks (the relative error range is from 23% to 1146%). It was proposed to study empirical correlations separately for different types of rocks. It is concluded that general empirical equations should not be used for design and planning purposes until they have been tested on at least one rock sample from the production site, as they may contain unacceptably large errors.

In paper [20], changes in the ultrasonic and mechanical properties of the rock are studied using velocity measurements of ultrasonic waves on limestone containing natural cracks and lamination, subjected to uniaxial compression tests. The results showed that these heterogeneities reduce the speed of ultrasonic waves and the mechanical strength of limestone. In combination with the analysis of X-ray images of the studied samples, it was found that the orientation of the layering and pre-existing penetrating cracks affects the direction of the subsequent crack propagation under uniaxial compressive load. According to the test results, the studied limestones were divided into four types: fissured-layered, filled cracks and lamination, basic filled cracks and almost intact.

In papers [21, 22], the focus was on the importance of selecting and using ultrasonic transducers for rock characterisation. It is theoretically and experimentally proved that the influence of various parameters of the transducer on the results of measurements of the speed of ultrasound is an indicator of changes in the characteristics of the test sample. It is concluded that the existing standards do not contain sufficient practical recommendations on several issues and require consideration of the proposed changes [23].

Modern methods of analysis and interpretation of information are widely used in processing the results of ultrasonic measurements [24–26]. In paper [27], it was suggested to use cluster and quantitative analysis of various characteristic features of ore-forming minerals for the classification of processed iron ore into blocks. As a result, ore material that requires higher degrees of enrichment was identified.

Thus, the existing technologies of ultrasonic measurements make it possible to evaluate various characteristics of rocks. However, due to the diversity and complexity of their structural and textural formations, it is rather difficult to identify unambiguous dependences of the ultrasound propagation process about their specific geological and mineralogical varieties.

3. RESEARCH METHODS

At the mining and beneficiation plants, the processed ore is classified according to the main chemical and mineralogical, physical and mechanical characteristics into separate varieties. This division is used in the process of planning and organisation of ore mining in order to ensure a constant value of certain ore characteristics for the required time interval.

The most important stages required to solve this task include the identification, analysis and classification of distinctive features of various mineralogical-technological types of ore and minerals included in their composition.

Depending on the conditions of their formation and distribution, rocks have their inherent structural and textural features. They are characterised by a certain set of physical properties: porosity, permeability, density, elasticity, electrical resistivity, radioactivity, etc. [28].

Some physical and chemical properties of rocks can be studied in the conditions of their natural occurrence in the process of drilling exploratory and production wells by conducting appropriate geophysical surveys in them using the logging method.

Various types of logging are known [28–30], each of which has certain advantages and disadvantages. Fig. 1 shows a diagram of ultrasonic well logging, which is widely used in practice.

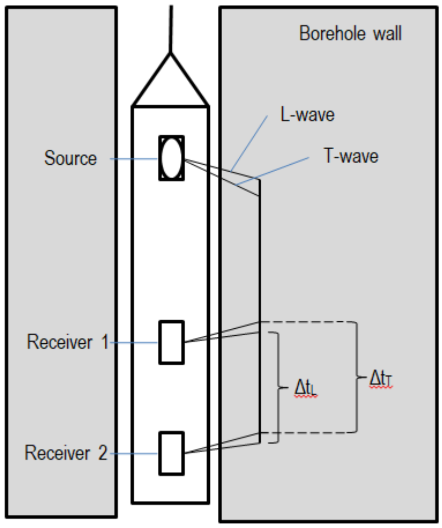

Fig. 1. Scheme of ultrasonic well logging

In the papers [31, 32], it is noted that as a result of ultrasonic well logging, speed and attenuation of ultrasonic waves in ore can be obtained. In turn, these parameters can be used to estimate the density and elastic qualities of the ore.

In rocks, the propagation speed of elastic waves varies widely and depends on physical properties, structure, texture, condition and other internal and external factors. The propagation velocities of elastic waves in an unbounded elastic medium can be determined by the formulas derived from the wave equations [33]. The velocity of the longitudinal wave in the studied volume is

$$C_L = \sqrt{\frac{E}{\rho}\frac{1-\sigma}{(1+\sigma)(1-2\sigma)}} \quad (1)$$

where the medium is assumed to be isotropic, ρ is its density, E is Young's modulus, and σ is Poisson's ratio.

The speed of transverse wave propagation is equal to

$$C_T = \sqrt{\frac{E}{\rho}\frac{1}{2(1+\sigma)}} = \sqrt{\frac{G}{\rho}}, \quad (2)$$

where G is the shear modulus.

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The ratio of the speed of longitudinal waves to the speed of transverse waves depends only on the Poisson ratio of the rock:

$$\frac{C_L}{C_T} = \sqrt{2\frac{1-\sigma}{1-2\sigma}} \,. \tag{3}$$

In turn, all the elastic characteristics of rocks are connected by the following equations:

$$G = \frac{E}{2\cdot(1+\sigma)} \,, \tag{4}$$

$$K = \frac{E}{3\cdot(1-2\cdot\sigma)} \,, \tag{5}$$

where K is the volume modulus of elasticity (module of comprehensive compression), proportional to the ratio of stress under uniform comprehensive compression to the elastic relative change in the volume of the sample.

In contrast to the propagation speed of elastic waves, the damping coefficient is determined by significant frequency dependence. In a wide range of frequencies – from 1 Hz to 10 MHz, the attenuation coefficient of various rocks varies from 1×10^{-8} to 2×10^{2} m^{-1}. The attenuation decrement in the same frequency range varies from 1×10^{-2} to 1.0 on average α [34, 35].

The attenuation coefficient increases with increasing frequency. However, a clearly defined and unambiguous functional dependence of attenuation on frequency for rocks has not been established. For example, in granites in the frequency range from 10 kHz to 1000 kHz, the best approximation is observed when describing the frequency dependence by the quadratic function $\alpha = mf^2$, where m is the proportionality factor. In gabbro-diabases, quartzites, granito-gneisses, sandstones, slates and other rocks, the frequency dependence in the interval from 500 kHz to 5,000 kHz follows the law $\alpha = A_1 f + A_2 f^2$. This dependence is observed for both longitudinal and transverse waves α [34, 35].

The influence of the texture and intergrain boundaries on the attenuation coefficient is manifested in the fact that the value of this parameter, for example, in a single crystal is at least an order of magnitude lower than in a rock consisting of a given mineral. At low frequencies, ultrasound absorption prevails over scattering, so in this case, the radiation field is formed mainly by non-scattered acoustic vibrations. But even at high frequencies, there are regions where non-scattered radiation prevails over scattered radiation. This happens at short distances from the radiation source. Otherwise, the contribution of scattered radiation becomes significant. With an increase in frequency, the cross-section of the scattering of ultrasonic waves on mineral grains increases sharply. In this case, the radiation field is formed by both unscattered and scattered waves.

The ore bodies of the Kryvyi Rih iron ore basin (Ukraine) are divided into rich and poor. The texture of rich ores is shale-like and layered. The poor ones are represented by a series of layers of ferruginous quartzites with alternating ore and non-ore interlayers, usually 1–5 mm thick [36]. The ore layers are predominantly composed of martite, magnetite, hematite and hydrogoethite with minor amounts of quartz, chlorite and amphibole. Non-metallic interlayers consist of fine-grained quartz and contain inclusions of magnetite or martite. The iron content is 25%–45%. Rich ores (hematite and martite minerals) contain Fe >50% [36]. Average content is Fe = 46%–48%, S = 0.005%, Mn <0.45%, P = 0.02%–0.09%, SiO2 = 14%.

Fig. 2 shows the main mineral formations of the Kryvyi Rih iron ore basin [36].

Fig. 2. Formations of magnetite (black) with other minerals (enlarged 40 times): (a) interspersed structure of magnetite grains; (b) replacement of magnetite with quartz; (c) relics of quartz and iron mica in the magnetite layer; (d) folded jaspilite; (e) development of cummingtonite in the ore layer; (f) replacement of magnetite with aegirine

Tab. 1 provides information on the main textural features of the most common geological and mineralogical varieties of iron ores mined and processed by magnetic enrichment at the Southern Mining and Processing Plant in Kryvyi Rih.

The analysis of the given textural and structural features of the geological and mineralogical varieties of iron ores led to the conclusion that it is possible to identify them by ultrasonic sounding, taking into account the size distribution of inclusions of individuals and aggregates of the minerals that make them up. For this purpose, it is proposed to evaluate the scattering of ultrasound on these formations.

Let us assume that a single disk source located in the plane $z = z_0$ produces a directed beam of ultrasonic waves as it is shown in Fig. 3. Such a unit source of acoustic vibrations can be described by the radiation density

$$S_\lambda(\vec{r},\vec{\Omega}) = \delta(z-z_0)\cdot\frac{\delta(\cos\nu-1)}{2\pi}\cdot\frac{\mathrm{St}(a-\rho)}{\pi a^2} \tag{6}$$

where $\cos\nu \equiv \vec{\Omega}\circ\vec{u}_z$, $\vec{u}_z$ is the unit vector directed along the z-axis, $\rho = \sqrt{x^2+y^2}$, a is the radius of the disk source, $\delta(x)$ is the Dirac impulse, and $\mathrm{St}(x)$ is Heaviside's unit step function:

$$\mathrm{St}(x) = \begin{cases} 1 & \text{for } x > 0 \\ 0 & \text{for } x < 0 \end{cases} \,. \tag{7}$$

When a wave passes through a medium containing a large number of randomly located particles, the phases of waves scattered in any given direction and coming from randomly located centres are incoherent. As a result, the total intensity of the ultrasonic wave at a given point is equal to the sum of the intensities of the waves coming from all scattering centres. The scattering cross-sections in this case are additive, so the linear absorption and scattering coefficients, $\Sigma_c(\lambda)$ and $\Sigma_S(\lambda)$, respectively, can be determined by the formulas:

$$\Sigma_c(\lambda) = n\sigma_c(\lambda)\,,\ \Sigma_S(\lambda) = n\sigma_S(\lambda)\,. \tag{8}$$

Tab. 1. Characteristics of the mineral composition, as well as the size of individuals and aggregates of the Skelevatsky magnetite deposit (YUGOK)

Hornfels and jaspilites	Layer types	Magnetite			Quartz	
		Size (mm)		Content (%)	Grain size (mm)	Content (%)
		Grain	Unit			
Magnetite	Ore	0.15	0.35	90	0.04	8.5
	Mixed	0.11	0.18	37.5	0.04	59.5
	Nonmetallic	0.06	0.00	3	0.07	95
Chlorite–carbonate–magnetite	Ore	0.18	0.45	85	0.05	8
	Mixed	0.12	0.20	22	0.06	53.5
	Nonmetallic	0.05		2.5	0.075	73
Hematite–magnetite	Ore	0.15	0.6	87	0.03	5.5
	Mixed	0.12	0.33	38	0.05	55.6
	Nonmetallic	0.08	0.1	1.8	0.06	92
Magnetite–cummingtonite–chlorite–siderite	Ore	0.15	0.2	76	0.08	4
	Mixed	0.07	0.12	10.7	0.06	49.6
	Nonmetallic	0.04		5	0.1	52

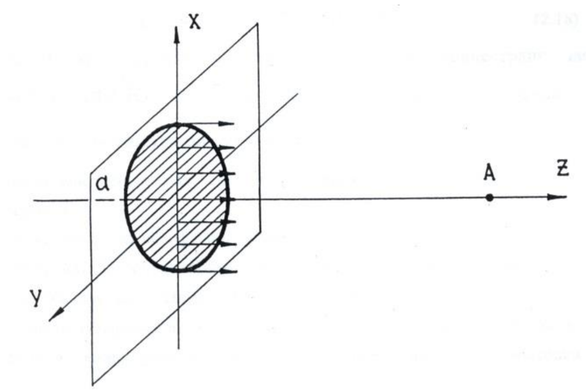

Fig. 3. Spatial orientation of the disk emitter of ultrasonic vibrations

Here, λ is the wavelength, n is the concentration of particles (number of particles per unit volume) and $\sigma_c(\lambda)$ and $\sigma_S(\lambda)$ are the respective total cross-sections for absorption and scattering of the acoustic wave by a single particle.

The field generated by the emitter of ultrasonic vibrations in the elementary volume of the phase space is described by the expression:

$$\vec{\Omega}\nabla I_\lambda(\vec{r},\vec{\Omega}) = -\Sigma(\lambda)\cdot I_\lambda(\vec{r},\vec{\Omega}) + \\ + \iint \Sigma_S(\vec{\Omega}'\to\vec{\Omega})\cdot I_\lambda(\vec{r},\vec{\Omega}')\mathrm{d}\Omega' + S_\lambda(\vec{r},\vec{\Omega}) \,, \tag{9}$$

where $S_\lambda(\vec{r},\ \vec{\Omega})$. The phase coordinates are the set of variables $\vec{r}$ and $\vec{\Omega}$, and the elementary phase volume is determined by the product $\mathrm{d}\vec{r}\circ\mathrm{d}\vec{\Omega}$. The meaning of this equation is as follows: the change in the intensity of the ultrasonic beam $I_\lambda(\vec{r},\ \vec{\Omega})$ having a direction $\vec{\Omega}$ at the point $\vec{r}$ occurs, first, due to its weakening – absorption and scattering (the first term on the right-hand side); second, due to the scattering of the energy flow, which previously had a direction $\vec{\Omega}'$, in the direction $\vec{\Omega}$ (the second term on the right-hand side); and finally, due to the energy arriving in this beam from sources (the last term on the right side).

When ultrasonic waves propagate in a rock mass, the radiation field is formed by both unscattered and scattered waves. Correct calculation of the radiation field of scattered waves is a difficult task. To estimate the main characteristics of scattered radiation, we restrict ourselves to estimating the contribution of singly scattered ultrasonic waves.

From expression (9), kinetic equation can be obtained, the solution of which is the function $I_\lambda(\vec{r},\ \vec{\Omega})$:

$$I^s_\lambda(\vec{r},\vec{\Omega}) = \\ = \int\left(\iint \Sigma_S(\vec{\Omega}'\to\vec{\Omega})\cdot\frac{e^{-\tau(\vec{r}',\vec{r},\lambda)}}{|\vec{r}-\vec{r}'|}\cdot\delta\Big(\vec{\Omega}-\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|}\Big)\cdot I^\circ_\lambda(\vec{r}',\vec{\Omega}')\mathrm{d}\vec{\Omega}'\right)\circ\mathrm{d}\vec{r}' \tag{10}$$

Then the integral intensity of singly scattered waves is determined by the expression:

$$I^s_\lambda(\vec{r}) = \iint_{4\pi} I^s_\lambda(\vec{r},\vec{\Omega})\mathrm{d}\Omega \,. \tag{11}$$

Substituting the right-hand side of expression (10) into (11) and integrating, we obtain the following:

$$I^S_\lambda(\vec{r}) = \int\iint \Sigma_S\Big(\vec{\Omega}'\to\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|}\Big)\cdot\frac{e^{-\tau(\vec{r}',\vec{r},\lambda)}}{|\vec{r}-\vec{r}'|}\cdot I^\circ_\lambda(\vec{r}',\vec{\Omega}')\mathrm{d}\vec{\Omega}'\circ\mathrm{d}\vec{r}' \,. \tag{12}$$

Let us estimate this value at point *A* on the axis of the ultrasonic beam (Fig. 3). We write expression (12) in a cylindrical coordinate system:

$$I^S_\lambda(z) = 2\pi\int_0^z\int_0^a I^\circ_\lambda e^{-\Sigma z'}\Sigma_S(\mu)\frac{e^{-\Sigma\xi}}{\xi^2}\rho'\mathrm{d}\rho'\mathrm{d}z' \tag{13}$$

where $\vec{\xi} = \vec{r}-\vec{r}'$, $\xi = |\vec{\xi}| = \sqrt{(z-z')^2+\rho'^2}$, and $\mu = \vec{u}_z\circ\vec{u}_\xi$ with $\vec{u}_\xi = \vec{\xi}/\xi$ (unit vector in the direction of $\vec{\xi}$).

To calculate (13), we will make several approximations. First, in the far field, $z \gg a$ and therefore $\xi \approx z - z'$. Second, the scattering of particles is assumed to be isotropic, and then

$$\Sigma_S(\vec{\Omega}\to\vec{\Omega}') = \frac{n\sigma_S(\lambda)}{4\pi} \,. \tag{14}$$

Taking these approximations into account, integrating in (13), we obtain the following:

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$$I_{\lambda}^{S}(z)=\frac{n\sigma_S(\lambda)}{4}e^{-\Sigma(\lambda)z}I_{\lambda}^{\circ}\left\{z\ln(1+\frac{a^2}{z^2})+2a\cdot\arctan\frac{z}{a}\right\}. \quad (15)$$

The solution of Eq. (15) can be obtained by a numerical method, for example, the Monte Carlo method [33].

To solve practical problems, we will evaluate the scattered radiation by measuring the attenuation of the probing pulse at a fixed angle to the central axis of propagation of the ultrasonic beam and compare the obtained values with the exemplary ones.

4. RESEARCH RESULTS

The results of the analysis of the five main mineralogical and technological varieties of ores, which are mined and received for processing from one of the deposits of the Kryvyi Rih iron ore basin, are given in Tab. 2.

Tab. 2. The results of the analysis of different types of ores

Ore variety	Content (%)				Density (kg/m³)
	Quartz	Magnetite	Hematite	Siderite	
1	63.7	30.9	1.4	3.8	3,431
2	68.4	21.7	0.4	9.1	3,248
3	64.5	30.2	1.5	3.8	3,414
4	74.6	4.5	0.7	20.2	2,989
5	60.8	31.4	5.4	2.5	3,530

The following designations of ore varieties are used [37]: 1 – magnetite horns; 2 – silicate–carbonate–magnetite hornblende; 3 – red-striped magnetite and hematite–magnetite hornblende; 4 – silicate slates, ore-free hornblende and quartz; 5 – hematite–magnetite hornblendes.

Magnetite, hematite and siderite, which are part of the ore particles, differ in density, elastic qualities and textural–structural manifestations (Tab. 1), and the ore particles of different mineralogical and technological varieties differ in the content of these components (Tab. 2). For operational recognition of ore varieties, the results of following measurements were used: transverse C_T and longitudinal C_L propagation speed, total attenuation α and scattering of ultrasonic waves in the studied environment. Tab. 3 shows the statistical parameters of the aforementioned parameters.

Tab. 3. Statistical characteristics of measured ultrasonic wave propagation parameters in the studied environment

Parameters	Min	Max	Mean	Variance
α (dB/m)	23	44	35	563
α_1 (dB/m)	28	56	48	1,624
C_L (m/s)	4 144	5 714	4 768	401 339
C_T (m/s)	2 343	2 857	2 652	40 868

Fig. 4 shows the obtained interdependencies of rock characteristics, while Fig. 5 shows simultaneous dependences of transverse C_T and longitudinal velocity C_L of ultrasound on rock characteristics. Each point on Figs. 4 and 5 represents the average value obtained as a result of the experiment series

It should be noted that in the case when the propagation speeds of elastic waves in the studied rocks change by 25%–40%, their attenuation and scattering coefficients change by several times.

Based on the fairly compact location of the obtained measurement results in the space of indirect features, it was concluded that their division into mineralogical-technological varieties should be represented by means of fuzzy clustering. In this case, the properties of the ore sample were characterised by a fuzzy membership function, which takes values in the range from 0 to 1.

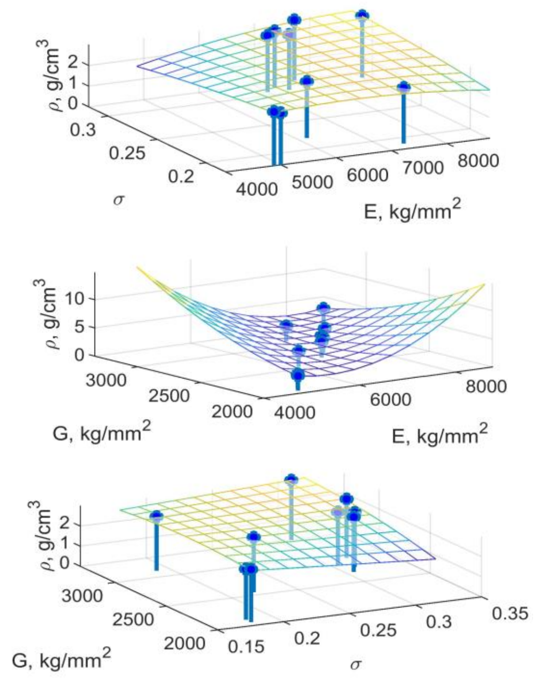
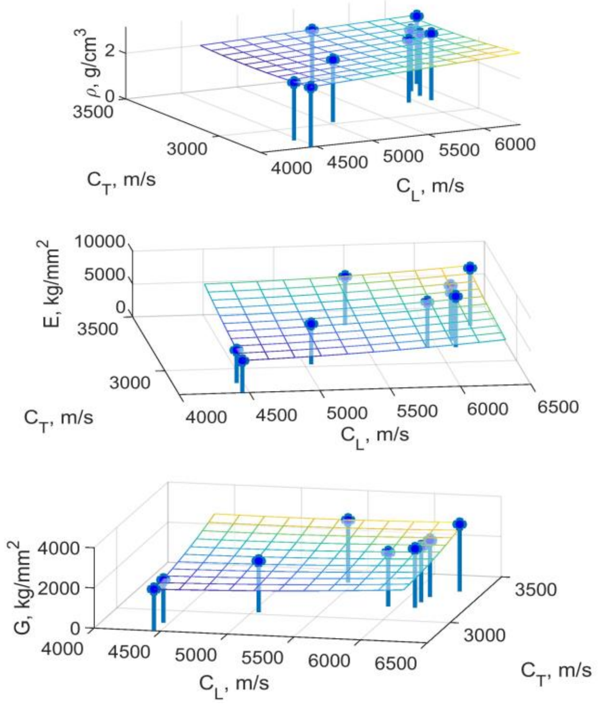


Fig. 4. Interdependencies of rock characteristics



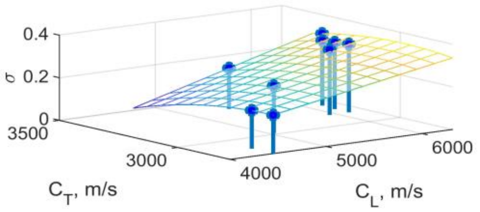


Fig. 5. Interdependencies of the speed of transverse ultrasonic waves Ct and the speed of longitudinal ultrasonic waves Cl and rock characteristics

Fuzzy clusters are described by a fuzzy partition matrix [38]:

$$F = [\mu_{ki}], \mu_{ki} \in [0,1], k = \overline{1,M}, i = \overline{1,c}, \tag{16}$$

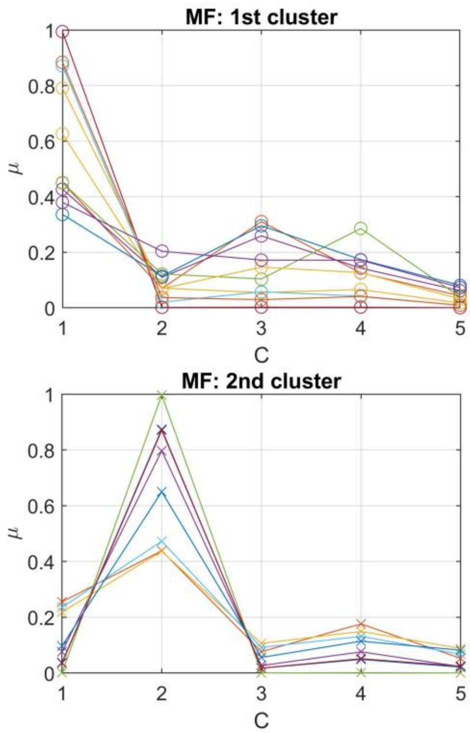
where the line with the number k contains the degrees of membership of the object $(x_{k1}, x_{k2}, \ldots x_{kn})$ to the corresponding clusters $A_1, A_2, \ldots, A_c$. The fuzzy C-means clustering algorithm that was used to divide the characteristics of ore samples into groups is based on the minimisation of the C-means functional [38]:

$$J(X;U,V) = \sum_{i=1}^{c}\sum_{k=1}^{N}(\mu_{ik})^m \|x_k - v_i\|_A^2 \to \min, \tag{17}$$

where μ_{ik} is the degree of ownership of the element x_k to cluster v_i and $V = [v_1, v_2, \ldots, v_c], v_i \in R^n$ is a vector of cluster centres:

$$D_{ikA}^2 = \|x_k - v_i\|_A^2 = (x_k - v_i)^T A_i (x_k - v_i). \tag{18}$$

It was established that in the process of clustering, the results of measurements of the characteristics of the five studied mineralogical-technological varieties of ore, an average of 22 iterations must be performed, and the value of the objective function (17) is equal to 1.1562. Fuzzy functions belonging to the characteristics of ore samples that were assigned to a certain cluster, a given cluster and other clusters are presented in Fig. 6.



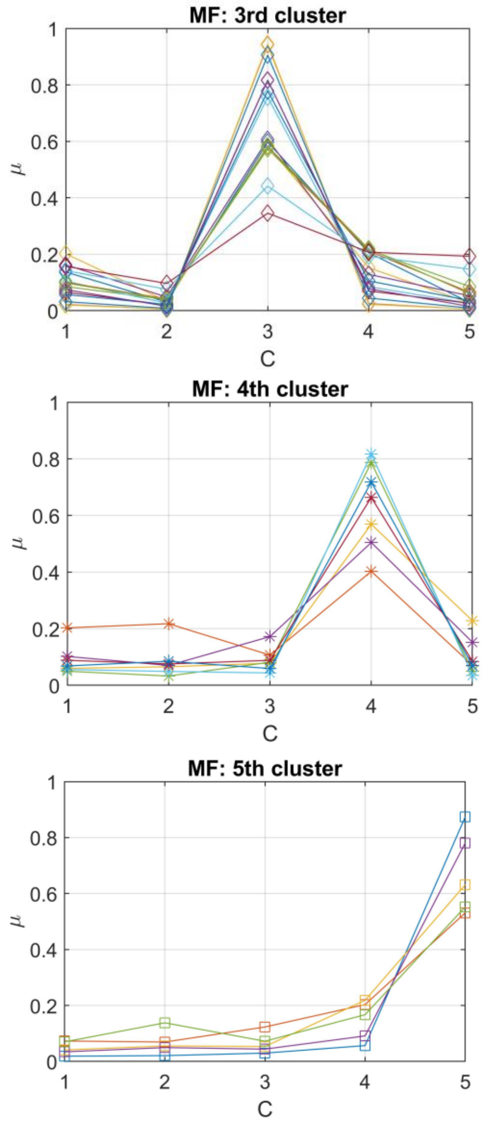


Fig. 6. Functions of points belonging to individual clusters

The analysis of the obtained results of fuzzy clustering showed that the obtained distribution of the results of ultrasonic measurements into clusters corresponds to the results of the system of classification of ores by mineralogical and technological varieties adopted at this enterprise and ensures the accuracy of their operational recognition in the mining process by at least 91.3%.

The frequency dependence of the ultrasound attenuation coefficient on the characteristics of the rock allows us to conclude about the prospects of using this parameter to improve the results of identification of its geological and mineralogical structures.

When performing technological tests of the proposed method, a mobile installation for well logging "Karrier-Kryvbas" was used, as well as a portable device for determining the content of iron in ore "PAKS-4KK" [40]. The acoustic measuring channel consists of sub-blocks for the formation, generation, reception, frequency and time selection of ultrasonic waves of the "Pulsar" granulometer of our development.

The preparation of ore samples (cores) and the study of their chemical composition were carried out using methods that are regulated and used at Ukrainian mining and mining processing plants in accordance with the State Standards of Ukraine. The chemical composition of the samples was studied with the help of

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chemical and phase chemical analyses, studies under a microscope in transmitted and reflected light, as well as with the use of a diffractometer (X-ray diffraction, XRD) and an X-ray fluorescence (XRF) analyzer. The quantitative mineral composition of the studied ore samples was calculated based on the results of chemical and phase analyses. The actual density was measured by the pycnometric method.

5. CONCLUSIONS

Texture and combinations of minerals with different physical–mechanical and chemical–mineralogical properties are prerequisites for identifying the main mineralogical and technological varieties of iron ore by ultrasonic measurements. To take into account the textural features of the minerals that make up iron ore and their aggregations, it is proposed to evaluate the scattering of ultrasound on these formations.

The fuzzy clustering of measured transverse and longitudinal speeds of propagation, CT and CL, respectively, on the one hand and the estimated total and scattering-induced attenuation of ultrasonic waves in the studied environment, α and α1, respectively, on the other hand correspond to the results of the accepted system of classification of ores into mineralogical and technological varieties: magnetite corneas; silicate–carbonate–magnetite hornblende; red-striped magnetite and hematite–magnetite hornets; silicate slates, ore-free hornblende and quartz; and hematite–magnetite hornblendes. This ensures the accuracy of their operational recognition in the mining process with at least 91.3%.

A further direction of research is the use of the frequency dependence of the ultrasound attenuation coefficient on the characteristics of the rock to improve the results of identification of its geological and mineralogical structures.

REFERENCES

1. Zak A. Global Iron Ore Market to Reach 2.7 Billion Metric Tons by 2026. Global Industry Analysts (Internet). 2022. Available from: https://www.prnewswire.com/news-releases/global-iron-ore-market-to-reach-2-7-billion-metric-tons-by-2026--301497721.html.
2. Falagán C, Grail BM, Johnson DB. New approaches for extracting and recovering metals from mine tailings, Miner Eng. 2017;106:71–8. 10.1016/j.mineng.2016.10.008.
3. Golik V, Komashchenko V, Morkun V, Zaalishvili V. Enhancement of lost ore production efficiency by usage of canopies, Metall Mining Ind. 2015;7(4):325–9.
4. Henckens T. Scarce mineral resources: Extraction, consumption and limits of sustainability. Resour Conserv Recy. 2021;169(105511): 1–12. 10.1016/j.resconrec.2021.105511.
5. Morkun V, Semerikov S, Hryshchenko S, Slovak K. Environmental geo-information technologies as a tool of pre-service mining engineer's training for sustainable development of mining industry. CEUR Workshop Proc 1844. 2017;303–10.
6. El Abassi D, Faiz B, Ibhi A, Aboudaoud I. A new ultrasound method for measuring the physical and mechanical properties of rocks. J Environ Eng Geophys. 2016;21(1):29–36. 10.2113/JEEG21.1.29.
7. Bhave V, Chimankar OP, Dhoble SJ. Determination of compressive strength of rocks using ultrasound. AIP Conf Proc. 2104 (ICMBAT 2018). 2019;(020035):1–8. 10.1063/1.5100403.
8. Morkun V, Morkun N, Pikilnyak A. Iron ore flotation process control and optimization using high-energy ultrasound. Metall Mining Ind. 2014;6(2):36–42.
9. Ishimoto T, Suetoshi R, Cretin D, Hagihara K, Hashimoto J, Kobayashi A, Nakano T. Quantitative ultrasound (QUS) axial transmission method reflects anisotropy in micro-arrangement of apatite crystallites in human long bones: A study with 3-MHz-frequency ultrasound. Bone. 2019;127:82–90. 10.1016/j.bone.2019.05.034.
10. Oelze ML. Statistics of scatterer property estimates. In: Mamou J, Oelze ML. Quantitative Ultrasound in Soft Tissues. Springer, Dordrecht etc. 2013:43–69.
11. Morkun V, Morkun N, Tron V. Distributed control of ore beneficiation interrelated processes under parametric uncertainty. Metall Mining Ind. 2015;7(8):18–21.
12. Zagzebski JA, Rosado-Mendez IM, Nasief HG, Hall TG. Quantitative ultrasound: Enhancing diagnosis using estimates of acoustic attenuation and backscatter. AIP Conf Proc 1747 (Medical Phys). 2016;(050001):1–10. 10.1063/1.4954108.
13. Dunn MJ. Quantifying uncertainty in mining geomechanics design. Proc First Int Conf Mining Geomech Risk (MGR 2019). 2019;391-402. 10.36487/ACG_rep/1905_23_Dunn.
14. Golik V, Komashchenko V, Morkun V, Gaponenko I. Improving the effectiveness of explosive breaking on the bade of new methods of borehole charges initiation in quarries. Metall Mining Ind. 2015;7(7):383–7.
15. Garia S, Pal AK, Ravi K. Elastic wave velocities as indicators of lithology-based geomechanical behaviour of sedimentary rocks: an overview. SN App Sci. 2020;2(1521):1–21. 10.1007/s42452-020-03300-1.
16. Soroush H, Qutob H. Evaluation of rock properties using ultrasonic pulse technique and correlating static to dynamic elastic constants. Proc 2nd South Asain Geosci Conf Exhibition (GEO India 2011). 2011:1–12. Available from: http://www.mkckorea. com/catalog/qseeman/UC-170/correlating_static.pdf.
17. Arsyad M, Tiwow VA, Sulistiawaty, Sahdian IA. Analysis of physical properties and mechanics of rocks in the karst region of Pangkep Regency. J Phys:Conf Ser. 2020;1572(012008):1–8. 10.1088/1742-6596/1572/1/012008.
18. Morkun V, Morkun N, Tron V. Distributed closed-loop control formation for technological line of iron ore raw materials beneficiation. Metall Mining Ind. 2015;7(7):16–9.
19. Chawre B. Correlations between ultrasonic pulse wave velocities and rock properties of quartz-mica schist. J Rock Mech Geotech Eng. 2018;10(3):594–602. 10.1016/J.JRMGE.2018. 01.006.
20. Zuo JP, Wei X, Shi Y, Liu C, Li M, Wong RHC. Experimental study of the ultrasonic and mechanical properties of a naturally fractured limestone. Int J Rock Mech Mining Sci. 2020;125(104162). 10.1016/j.ijrmms.2019.104162.
21. Bartoszek S, Stankiewicz K, Kost G, Ćwikła G, Dyczko A. Research on ultrasonic transducers to accurately determine distances in a coal mine conditions. Energies. 2021;14(2532). 10.3390/en14092532.
22. Cerrillo C, Jiménez A, Rufo M, Paniagua J, Pachón FT. New contributions to granite characterization by ultrasonic testing. Ultrasonics. 2014;54(1):156–67. 10.1016/j.ultras.2013.06.006.
23. Basu A, Aydin A. Evaluation of ultrasonic testing in rock material characterization. Geotech Test J. 2006;29(2):117–25. 10.1520/GTJ12652.
24. McClements DJ. Ultrasonic Measurements in particle size analysis. In: Meyers, RA. Encyclopedia of Analytical Chemistry. Wiley Online. 2006. 10.1002/9780470027318.a1518.
25. Samaitis V, Jasiūnienė E, Packo P, Smagulova D. Ultrasonic methods. In: Sause MGR, Jasiūnienė E (eds.). Structural Health Monitoring Damage Detection Systems for Aerospace. Springer Nature, Cham, Switzerland. 2021;87–131. 10.1007/978-3-030-72192-3_5.
26. Morkun V, Morkun N. Estimation of the crushed ore particles density in the pulp flow based on the dynamic effects of high-energy ultrasound. Arch Acoust. 2018;43(1):61–7. 10.24425/118080.
27. De Villiers JPR, Lu L. XRD analysis and evaluation of iron ores and sinters. Iron Ore. 2015;85–100. 10.1016/B978-1-78242-156-6.00003-4.

28. Gerali F. Well Logging, Engineering and Technology History Wiki. 2019. Available from: https://ethw.org/Well_Logging.
29. Haldar SK. Mineral Exploration: Principles and Applications Elsevier, Amsterdam etc. Second ed. 2018.
30. Liu CR. Laterolog tools and array laterolog tools. In: Liu CR, Theory of Electromagnetic Well Logging. Elsevier, Amsterdam etc. 2017;579-624.
31. Khan K, Vantala A, Mohiuddin M. Dependence of ultrasonic velocities and dynamic elastic rock properties on stress and saturation changes. Proc Int Symp Soc Core Analysts. 2005;(SCA2005-64): 1–6.
32. Kenigsberg AR, Rivière J, Marone C, Saffer DM. A method for determining absolute ultrasonic velocities and elastic properties of experimental shear zones. Int J Rock Mech Mining Sci. 2020;130(104306). 10.1016/j.ijrmms.2020.104306.
33. Feynman R, Leighton R, Sands M. Sound. The wave equation. In: Lectures in Physics, vol 1, ch 47. Caltech. 2022. Available from: https://www.feynmanlectures.caltech.edu/I_47. html.
34. Acoustic properties of rocks [in Russian]. 2017. Available from: http://ctcmetar.ru/volnovye-processy/9297-akusticheskie-svoystva-gornyh-porod.html.
35. Acoustic velocity logging [in Russian]. 2019. Available from: http://fccland.ru/dobycha-nefti/6826-akusticheskiy-karotazh-po-skorosti.html.
36. Lazarenko YK. Mineralogiya Krivorozhskogo basseyna [Mineralogy of the Kryvyi Rih basin; in Russian]. Naukova dumka, Kyiv. 1977.
37. Koryakov-Savoyskiy BA, Gulenko TI, Lopatin VI. Issledovaniye izmel'chayemosti rud s tsel'yu razrabotki sredstv avtomatizatsii [Study of the grindability of ores in order to develop automation tools; in Russian]. Avtomatizatsiya gornorudnogo i metallurgicheskogo proizvodstva: NIIAchermet, 7.13–20.38. 1971.
38. Shtovba SD. Vvedeniye v teoriyu nechetkikh mnozhestv i nechetkuyu logiku [Introduction to the theory of fuzzy sets and fuzzy logic; in Russian]. 2014. http//matlab. exponenta.ru/fuzzylogic/book1.
39. Morkun V, Morkun N, Tron V, Hryshchenko S, Serdiuk O, Dotsenko I. Basic regularities of assessing ore pulp parameters in gravity settling of solid phase particles based on ultrasonic measurements. Arch Acoust. 2019;44(1):161–7. 10.24425/aoa.2019.126362.
40. Azarian A, Azarian V, Morkun V. Operational Quality Control of Ferrous Metal Ores. Lambert Academic Publishing, London, UK. 2022.

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Natalia Morkun: https://orcid.org/0000-0002-1261-1170
Gerhard Fischerauer: https://orcid.org/0000-0003-2000-4730
Vitalii Tron: https://orcid.org/0000-0002-6149-5794
Alona Haponenko: https://orcid.org/0000-0003-1128-5163