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Reducing industrial noise by the use of damping alloys when manufacturing mining equipment parts

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A R T I C L E I N F O

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Steel
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Damping
Sound radiation
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Noise intensity

A B S T R A C T

The existing experience of noise and vibration specialists has shown that the problem of noise reduction is very relevant, especially for the mining industry. Traditional methods of dealing with industrial noise are not effective enough. In solving this issue, it is advisable to reduce the noise level at the source of its occurrence through the use of metal alloys with enhanced dissipative properties. The article presents the results of experimental studies of developing steels with increased damping properties for manufacturing perforator parts: bit bodies and drill rods. In this article, the sound pressure level of alloys dependence on the type of heat treatment has been studied, and the optimal content of alloying elements has been established to ensure the development of the ferrite-pearlite structure. This structure is characterized by an increased dislocation density and is the reason for reducing the noise of the drill rod and the body of the perforator bit by 10–12 dB A. In addition, the article establishes the pattern of noise intensity at different frequency intervals for standard and developed alloys.

1. Introduction

Underground mining is one of the most dangerous areas of human labor activity and requires constant attention to the safety of miners. One of the harmful and dangerous production factors is the increased noise level, which in enclosed spaces increases many times and causes illness for miners up to hearing loss. The studies show that mentally stressed workers make almost twice as many mistakes in 70 dB noise than they do in silence. At the same time, the working capacity of those employed in mental labor falls by about 60%, and in physical labor by 30% [1]. Thus, the presence of a high level of industrial noise not only has a harmful effect on the human hearing organs but can also cause unintentional erroneous actions of personnel when making managerial decisions, operating technical devices, etc. and lead to emergencies and accidents at work [2].

Studying the noise sources in the mining industry shows that workplaces are dominated by medium and high frequency noise,

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which is 85–100 dB and often reaches 110–120 dB [1]. The development of pathology in workers is most typical for exposure to sound in the high frequency range (from 3000 to 6000 Hz). Prolonged exposure to excess sound levels leads to the disease progression [3,4]. The main source of pulse noise of impact origin is industrial equipment (hammer drills, pneumatic and hydraulic drill hammers, rotary percussion drilling machines with cutting crowns, excavators, drill rods, gears, ratchets, levers, pulleys, etc.). One of the noisiest machines in the mining industry are rock drills.

The perforator is a pneumatic percussion machine that automatically strikes the end of the drill rod while turning it.

In rotary hammers with automatic rotation of the drill, the shock-rotary mechanism is structurally made in the form of a piston engine that converts the energy of the compressed air supplied to the rotary hammer into the energy of the mechanical reciprocating motion of the piston-drummer. At the end of the working stroke, the piston-drummer transfers energy directly to the drill rod by striking the end face of its shank, and on the return stroke it works as a drive for the drill rod rotation mechanism.

In addition, the piston-drummer of the perforator is at the same time the main part of the air distribution system. So, it directly controls the exhaust of compressed air, the opening of the valve transfer channels (in systems with spool air distribution), determines the volume of the working chambers; in some designs of perforators, the piston-drummer performs all the functions of air distribution (without spool air distribution).

In the spectral analysis of the pneumatic perforator noise, two categories are distinguished: aerodynamic and mechanical noise. The first one is created by exhaust air, as well as by blowing the hole with compressed air. This noise is exacerbated by air leaks through gaps and leaks that increase as wear occurs during operation. During the operation of perforators, the main cause of aerodynamic noise is the periodic exhaust of the exhaust air. In many cases exhaust noise is a significant part of the total sound power perforator (approximately 50–60%). The sound power level of the exhaust depends on the frequency of blows and the power of the perforator (i.e., on the air flow), on the air pressure at the moment the exhaust starts, as well as the cross-sectional area and shape of the exhaust holes. With increasing the network air pressure, the exhaust noise increases. This noise refers mainly to the low-frequency region of the perforator sound radiation spectrum.

The sources of mechanical noise are impacts of the piston-drummer on the drill rod. The blows excite the rod vibration, the surface of which becomes a sound emitter with the power of 109–111 dB. Additional sources of mechanical noise include the noise of the ratchet mechanism, from the collision of the valve with the seats, splined mates, as well as that emitted by body parts. The level of mechanical noise of perforators is determined by the noise radiation of the drill rod (approximately 40–45%).

Pneumatic perforators designed for drilling boreholes and wells in the production of drilling and blasting operations are characterized by a very high noise level (120 dB). The use of solid drill rods provides higher productivity due to lower losses during the passage of the impact pulse, however, high-intensity noise up to 120–130 dB is generated [5].

The noise of mining equipment cannot be reduced either by sound absorption or sound insulation, or by the use of personal hearing protection. Therefore, the problem of reducing the noise of mining equipment, especially in underground mining, is very complicated, and studying the sources of industrial noise in order to develop technical solutions and improve process equipment is relevant.

This article presents the results of studying and developing alloys with increased damping properties for manufacturing perforator parts operating in the impact mode (drill rods and bit bodies) in order to reduce production noise at the source of its occurrence.

2. Materials and methods

For this study, experimental alloys have been smelted. At present, non-ferrous metals and alloys are mainly smelted in electric furnaces. During melting, explosions can occur due to the difference of the elements melting, which leads to burns and electric shock. Therefore, measures to improve working conditions in melting departments are always aimed at preventing accidents [6,7].

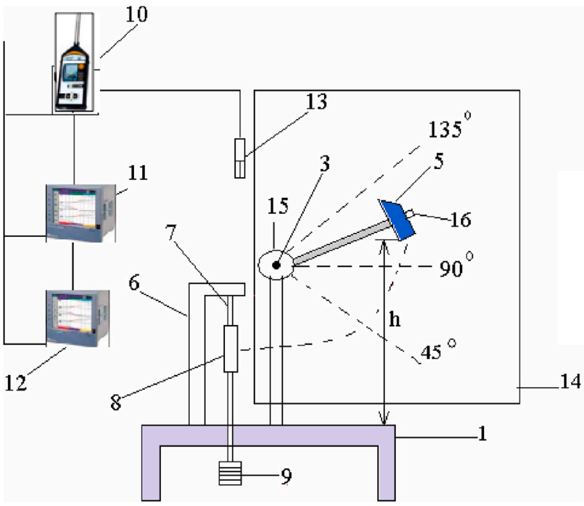

Fig. 1. KazNTU-2007 set for studying noise of metal flat samples collisions.

Experimental alloys have been melted in an LPZ-1-67 high-frequency induction furnace at the melting temperature t = 1700°C, the furnace power has been 70 kW. When performing the work, a graphite crucible was used.

For the purpose of further heat treatment, the smelted metal has been cast into molds with dimensions of 210 × 210 × 115 mm. The ingots have been subjected to forging, normalization, hardening and annealing. Forging was carried out at the temperature of 1200 °C. Normalization has been carried out according to the following mode: heating to A_{c3} +50 °C, holding within 1 h, and cooling in air. The hardening process consisted in heating the steel by 30–50 °C above the A_{c3} point for hypoeutectoid steel with the holding time of 30–40 min to complete phase transformations and subsequent cooling at the rate above the critical one. Quenching was carried out in oil. Heating was carried out in quartz ampoules (vacuum of the order of 10–3 at m.) muffle furnace. Annealing was carried out according to the mode: heating up to 920–970 °C, holding within 0.5 h, slow cooling.

Samples for studying acoustic characteristics have been cut using forged strips. The surfaces of the plates have been polished according to the 5th class of cleanliness. Dimensional deviations did not exceed 0.1 mm. Since manufacturing gears presents great difficulties and requires special equipment, all the samples for research were made in the form of a plate 50 × 50 × 5 mm in size.

To study the noise of collisions of the tested steels and alloys (from the set of N.I. Dreyman of 1968 to the KazNTU-2006 set, there was used the set for studying the impact sound KazNTU-2007 (Fig. 1) [8].

The KazNTU-2007 set includes the following elements: base (1); rack (2); axis (3); striker rod (4); drummer (5); specimen mounting bracket (6); sample attachment threads (7); sample (8); cargo (9); sound level meter (10); oscilloscope (11); recorder (12); microphone (13); striker deflection scale (14); retainer (15); nut (16).

The KazNTU-2007 set works as follows. Sample 8 is fastened in a plexus of tightly stretched threads 7 due to a relatively heavy load relative to the sample (load weight 20 kg). The drummer 5 deviates from the bottom point by a certain angle, which is determined both on the scale 14 and on the height h. Then the impactor is released and it falls under its own weight and makes a collision with the sample. The impact noise level is measured by an Oktava-101 A accurate pulse sound level meter (10); the impact process attenuation curve is recorded by oscilloscope (11) and recorder (12). After the impact, the striker is stopped by latch (15), protecting it from a second impact. Striker (5) is a hammer with a striker mass of 218 g. It is possible to deflect it at different angles from the equilibrium position. Four options were used in the work: when the striker deviates by 30° (h_1 = 7 cm), 45° (h_2 = 10 cm), 75° (h_3 = 12 cm), 90° (h_4 = 17 cm).

Steel plate samples (50 × 50 × 5 mm) were studied on the set. The sound pressure levels were studied in octave frequency bands in the range of 63–16000 Hz. The sound level is on the “A" scale. The sound pulse was recorded with an MK-102 capsule. This pulse is converted into an electrical signal amplified by the MK-102 preamplifier and fed to the input of an accurate pulse sound level meter 00017 from RFT (Germany) or an Oktava-101 A sound level meter (RF). The sound level meter indicator allows registering sound pressure levels from 30 to 130 dB with the accuracy of 0.5 dB. The block of octave filters OF-101 is designed to measure the frequency spectrum of an audio signal. Using a PSG-101 type recorder, the sound pulse was recorded over time. Recording was made on paper tape with a sapphire needle.

A sound generator ZG-10 was used to calibrate the measurements of the sound signal. Correction for changes in the sound signal from atmospheric pressure was carried out using a PF-101 pistonphone. The air temperature and humidity in the laboratory were kept constant.

Acoustic measurements were found as the average of five measurements. Before starting work, the measuring path was tuned by checking the sound pressure levels of the reference sample.

In the studies, standard structural steels 30HGSA, 45HhN, 18H2N4VA, 38HN3VA that are used for manufacturing perforator parts, have been selected as comparative samples. Steels (FK–1P, FK-2P, FK-3P, FK-4P) have been smelted as new damping alloys, the chemical composition of which differs from the standard cerium content (0.05–0.21%). To improve the damping properties, alloying elements are selected depending on how they change the structure of the alloy and how often they are used in the smelting of basic steels operating in the collision mode. Table 1 shows the chemical composition of standard and newly developed steels.

Table 1 shows that the carbon content of newly developed steels ranges from 0.32 to 0.48%, while for standard steels it is from 0.16 to 0.45%. The content of silicon, manganese, chromium and nickel is somewhat lower than that of the well-known standard steel grades. For example, the silicon content is from 0.19 to 0.88%; manganese from 0.35 to 1.31%; chromium from 0.35 to 1.68%; nickel from 0.29 to 3.75%, also cerium from 0.05 to 0.21%.

One of the alloys of standard steel 18H2N4VA contains Mo (0.14%), V (0.07%), W (0.87%) in its chemical composition. Therefore,

Table 1
Chemical composition of the studied alloys used for manufacturing the drill rod and the body of the drill bit.

Steel grade	Mass percent of each element, %								
	C	Si	Mn	Cr	Ni	Mo	V	W	Ce	Fe
30HGSA	0.35	0.97	1.34	1.20	0.31	–	–	–	–	the rest
45 H N	0.45	0.25	0.66	0.39	1.08	–	–	–	–	
18H2N4 VA	0.16	0.16	0.50	1.87	3.82	0.14	0.07	0.87	–	
38HN3VA	0.38	0.24	0.37	1.01	2.91	–	–	–	–	
FK-1P	0.32	0.26	1.31	0.35	0.29	–	–	–	0.1	
FK-2P	0.48	0.88	0.72	1.18	3.75	–	–	–	0.15	
FK-3P	0.38	0.19	0.48	1.68	2.88	0.11	0.09	0.77	0.05	
FK-4P	0.34	0.28	0.35	1.04	1.21	–	–	–	0.21	

a new FK-3P alloy containing similar elements Mo (0.11%), V (0.09%), W (0.77%) has also been developed for studies. In the FK-1P, FK-2P, FK-3P and FK-4P steels, one of the alloying elements is cerium, the content of which in the alloys under study is 0.1%; 0.15%; 0.05% and 0.21%, respectively. Alloying with rare earth metals is increasingly used in the production of cast iron, steel, and nonferrous metal alloys [9]. In this area, ferrocerium or "mischmetal" is mainly used as an alloying element: an electrolysis product of a mixture of salts of rare earth elements with a predominant content of cerium or cerium and lanthanum. The combination of alloying elements in iron-carbon alloys provides various structural modifications that determine the dissipation effect [10,11].

In addition to carbon, silicon, manganese, nickel and cerium, there were included Mo, V, W in the composition of the alloys, which, according to some authors, improve the damping properties of iron-carbon alloys. There are known works of complex alloying of iron-carbon alloys with silicon, manganese, nickel and chromium, but the content of these alloying elements differs from the content of the proposed alloys.

The mechanical properties of steels (according to GOST 4543–71) are shown in Table 2.

Table 2 presents the mechanical properties of steels 30HGSA, 45 H N, 18H2N4VA, 38HN3VA, FK-1P, FK-2P, FK-3P, FK-4P (σt, σv, δ5, ψ, αn, NV). Table 2 shows that the strength properties of the developed steels FK-1P, FK-2P, FK-3P, FK-4P are not inferior to standard steels. For example, the strength properties of 30HGSA is 1100 MPa, for the developed steels it ranges from 1040 to 1200 MPa.

3. Analysis of the acoustic characteristics of prototype steels

The steel samples have been subjected to heat treatment, and after each type of heat treatment, the acoustic characteristics of the alloys have been recorded. The sound pulse from the impact of the test sample with the striker has been measured not only with a sound level meter but also recorded using a PCS-500 storage oscilloscope that has been connected to a personal computer. Damping characteristics have been determined from the fixed signal on the monitor. Table 3 and Fig. 2 show the acoustic properties of the tested steel samples after hot forging.

When studying the acoustic characteristics of samples after hot forging presented in Tables 3 and it has been found that the noise emission of standard and developed alloys remains almost unchanged. The sound level varies from 97 to 110 dB A. Compared to standard alloys, the sound level of the FK-2P alloy decreased by an average of 4 dB A, and the sound pressure level decreased by an average of 2 dB. Such a decrease in sound emission can be explained by changing the structure of the alloy. Fig. 2 shows that the SPL peak is at frequencies of 8000–16000 Hz (108–109 dB), and the SPL minimum is at the frequency of 250–500 Hz (52–53 dB). At the same time, the damping alloy FK-2P stands out from all the alloys with its best acoustic performance: SPLFK-2 = 97 dB A; SPL1000 = 55 dB; SPL8000 = 93 dB; SPL16000 = 95 dB.

Table 4 and Fig. 3 show the acoustic characteristics of the test samples of steels after normalization. Table 4 shows that the most "voiced" alloys during collisions are 38HN3VA (113 dBA), 18H2N4VA (112 dBA), 45 H N (110 dBA). The FK-2P alloy (97 dBA) has the highest damping properties. Fig. 3 shows that the minimum SPL values were recorded at a frequency of 500 Hz (50–58 dB), the SPL peaks have been recorded at the frequency of 8000 and 16 000 Hz (94–110 dB). The reason for the high damping properties of the FK-2P alloy (0.88% Si; 0.72% Mn; 1.18% Cr; 3.75% Ni at 0.48% C and the rest of iron) after normalization is structural damping due to coarsening metal grains.

The acoustic characteristics of the studied steel samples after annealing are presented in Table 5 and Fig. 4. Table 5 shows that the sound pressure levels of the developed alloys in the frequency range in comparison with standard samples are lower by an average of 10 dB, and the sound level is by an average of 7 dB A. Among the developed samples, the FK-2P alloy also has the best acoustic characteristics.

In Fig. 4 it can be seen that the maxima of the sound pressure level in the octave bands of geometric mean frequencies are also at frequencies of 8000 and 16 000 Hz (92–112 dB), the minima are mainly at the frequency of 500 Hz (53–64 dB). At these frequencies, the sound pressure levels of standard samples are much higher (by 6–10 dB on average). The reason for this is formation of the pearlite-ferrite structure, which provides increased dissipation of sound energy.

The acoustic characteristics of the studied steel samples for the parts of the perforator after hardening are presented in Table 6 and Fig. 5.

Table 2
Mechanical properties of steels (acc. SS 4543–71).

Steel	Heat treatment mode (t ^{0}C)				σ_T	σ_B	δ	ψ	α_H, J/cm^2	HB After annealing, not higher than
	Hardening	Cooling medium	Tempering	Cooling medium	MPa		%			
					Not lower than					
30HGSA	880	oil	540	water or oil	850	1100	10	45	50	229
45 H N	820	water or oil	530	water or oil	850	1050	10	45	70	207
18H2N4 VA	950	oil	550	water or oil	850	1150	12	50	100	269
38HH3VA	850	oil	550	water	800	950	10	30	40	293
FK-1P	880	oil	540	water	845	1200	10	50	55	232
FK-2P	830	oil	530	water	860	1100	15	45	75	210
FK-3P	950	oil	550	water	842	1120	11	48	98	272
FK-4P	880	oil	550	water	880	1040	12	44	62	215

Table 3
Acoustic characteristics of prototype steels after hot forging.

Sample grade	Sound pressure level, dB, in octave bands with geometric mean frequencies, Hz									US, dBA
	63	125	250	500	1000	2000	4000	8000	16 000	
30HGSA	61	54	62	57	57	58	81	107	101	107
45 H N	61	55	62	58	65	62	81	106	103	106
18H2N4 VA	65	56	57	62	64	61	88	106	109	109
38HN3VA	62	60	58	56	57	62	83	108	107	110
FK-1P	65	57	59	56	59	65	87	106	105	107
FK-2P	58	55	56	56	55	62	80	93	95	97
FK-3P	60	55	52	53	56	60	79	96	98	100
FK-4P	61	59	55	57	59	64	82	105	103	106

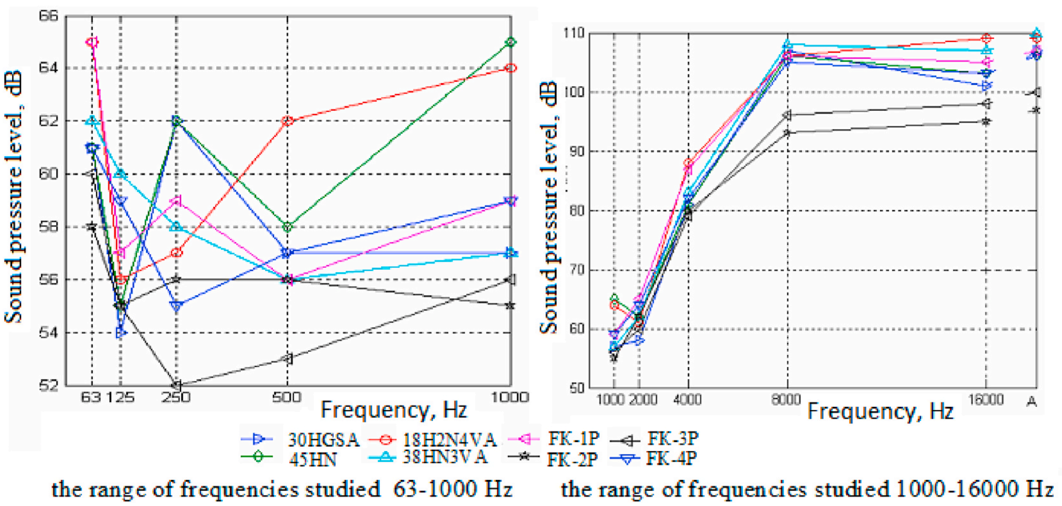

Fig. 2. Acoustic characteristics of sound emission of steels after hot forging.

Table 4
Acoustic characteristics of prototype steels after normalization.

Sample grade	Sound pressure level, dB, in octave bands with geometric mean frequencies, Hz									US, dBA
	63	125	250	500	1000	2000	4000	8000	16 000	
30HGSA	64	57	65	52	56	66	81	107	102	107
45 H N	60	64	57	57	57	61	80	107	109	110
18H2N4 VA	66	63	66	52	63	60	87	109	111	112
38HN3VA	62	56	57	58	62	67	86	110	110	113
FK-1P	64	51	56	51	55	61	81	100	105	107
FK-2P	57	52	55	50	56	63	79	95	94	97
FK-3P	58	57	59	53	55	62	82	97	97	100
FK-4P	62	56	58	54	54	61	81	104	106	107

Table 6 shows that the studied alloy FK-2P has the lowest sound level (91 dBA), which is 11–18 dB A lower than that of known similar steels ($SL_{30HGSA} = 102$ dB A, $SL_{45HhN} = 105$ dB A, $SL_{18H2N4VA} = 109$ dB A, $SL_{38HhN3VA} = 107$ dB A). Fig. 5 shows that SPL has the maximum at frequencies of 8000 Hz (88–108 dB) and 16 000 Hz (87–107 dB). The reduced values of the ultrasonic value of the FK-2P alloy (91 dBA) and the sound pressure levels in octave frequency bands characterize this alloy as damping. When this steel is heated by 30–50 °C above the A_{c3} point, the steel with the initial structure (pearlite + ferrite) acquires an austenitic structure that upon subsequent cooling at the rate above the critical one, turns into the martensitic structure, which reduces noise by 11–18 dB A.

During the microstructure investigation, a 3% solution of hydrochloric acid was used as an etchant. Let's consider the microstructure of the FK-2P alloy after all the types of heat treatment shown in Fig. 6. Microstructural analysis shows that after forging, local areas of pearlite are visible (Fig. 6, a), after normalization (Fig. 6, b), the balanced ferrite-pearlite structure, annealing led to grain growth (Fig. 6, c), quenching changes the structure to martensite with retained austenite (Fig. 6, d). The revealed structures are characterized by an increased density of dislocations, in addition, the developed alloys are ferromagnets, as a result of which the mechanism of domain dissipation of sound energy operates effectively.

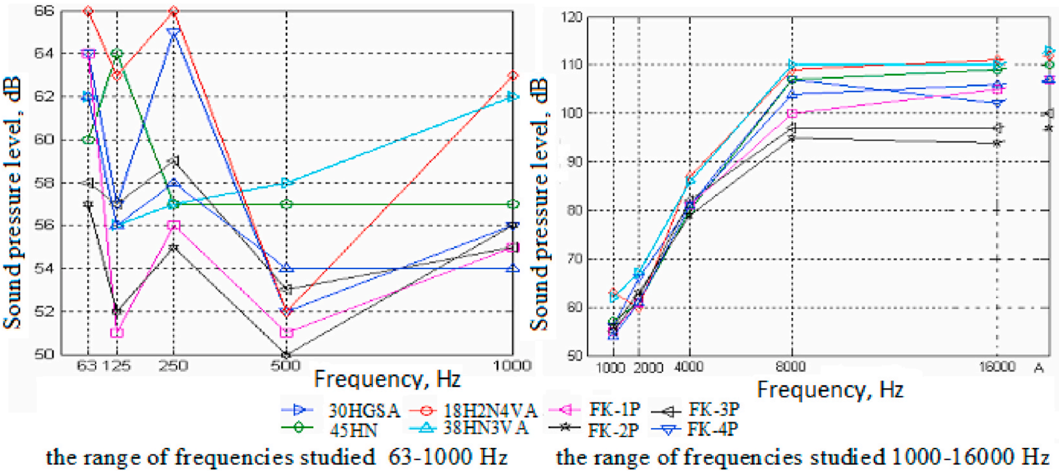

Fig. 3. Acoustic characteristics of sound emission of steels after normalization.

Table 5
Acoustic characteristics of test samples of steels for the drill rod and the body of the drill bit after annealing.

Sample grade	Sound pressure level, dB, in octave bands with geometric mean frequencies, Hz									US, dBA
	63	125	250	500	1000	2000	4000	8000	16 000	
30HGSA	63	66	58	57	64	66	80	104	102	105
45 H N	62	61	57	56	63	60	82	105	107	108
18H2N4 VA	63	68	62	64	58	67	88	119	110	112
38HN3VA	66	63	59	55	56	63	83	109	107	110
FK-1P	65	64	58	54	59	64	80	104	102	105
FK-2P	62	58	55	55	55	62	79	92	94	95
FK-3P	62	59	59	53	58	60	84	99	96	100
FK-4P	64	62	58	58	57	60	82	103	104	105

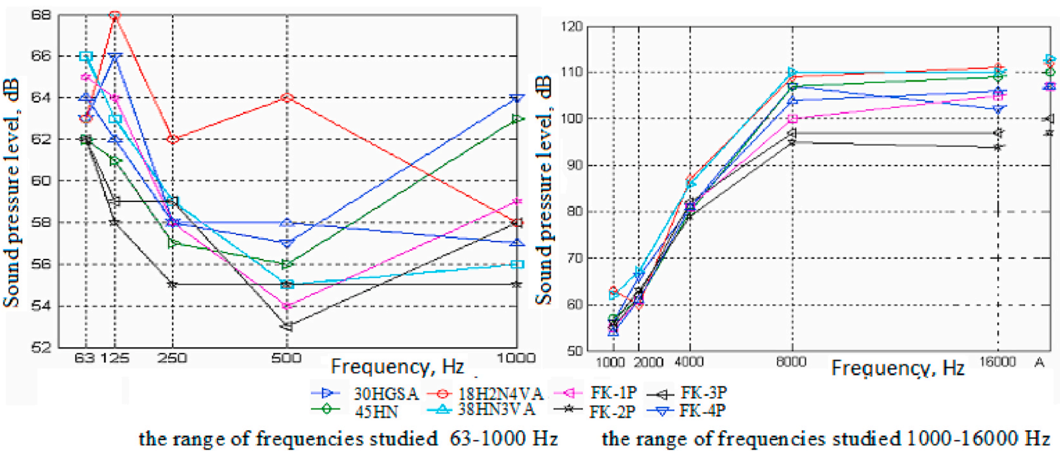

Fig. 4. Acoustic characteristics of sound emission of steels after annealing.

With increasing the content of carbon and alloying elements, the recrystallization temperature (700 °C; 0.5 h) increases, which leads to changing the shape of the ferrite grain that becomes oval or round with the size of 6–9 points (Fig. 6, c) [12]. In this case, the process of coagulation and spheroidization of cementite can occur, which worsens the strength properties of the alloy.

Heating the studied steels to the temperature (A_{c3} + 50 °C) leads to the formation of austenite, which, as a result of cooling, provides a fine-grained structure. Increasing the heating temperature above the A_{c3} point causes the austenite grain growth. With continued heating in the austenite region, the austenite grain will be crushed. Grain refinement, especially in alloyed steel, can be achieved by heating 100–300 °C above A_{c3}, which will lead to austenite recrystallization during the γ and α phase transformation, with

Table 6
Acoustic characteristics of prototype steels after hardening.

Sample grade	Sound pressure level, dB, in octave bands with geometric mean frequencies, Hz									US, dBA
	63	125	250	500	1000	2000	4000	8000	16 000	
30HGSA	68	63	637	65	58	61	88	98	100	102
45 H N	63	62	58	58	64	66	86	104	102	105
18H2N4 VA	69	68	58	66	57	68	80	107	107	109
38HN3VA	63	62	57	58	64	62	81	108	106	107
FK-1P	63	63	57	56	58	61	80	103	102	104
FK-2P	60	59	54	53	54	58	79	88	90	91
FK-3P	60	58	55	57	59	60	81	94	95	98
FK-4P	61	60	64	56	56	62	82	102	87	102

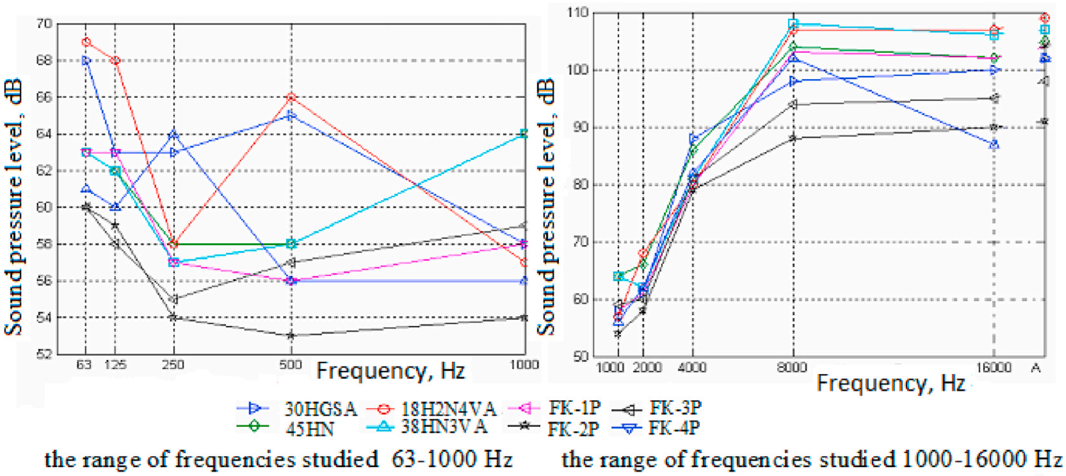

Fig. 5. Acoustic characteristics of sound emission of steels after hardening.

the formation of new austenite grains not related in orientation to the original structure.

The developed FK-2P steel containing chromium (1.18%), silicon (0.88%), manganese (0.72%), nickel (3.75%), cerium (0.15%) at the carbon content of 0.48% (the rest is iron), after heat treatment, provide the development of the ferrite-pearlite structure characterized by an increased dislocation density, which is the reason for reducing the noise of the drill rod and the body of the perforator bit by 10–12 dB A compared to those of standard steels, which improves working conditions due to acoustic comfort.

4. General regularity in changing the noise intensity at different frequency intervals for the developed alloys

With a sufficiently complete large experimental material, a natural question arises about the existence of a general regularity in changing the noise intensity at different frequency intervals for the known and developed alloys. Below there are the results of theoretical generalization of the laboratory experiments indicating the presence of this pattern and displaying it in a simplified form of a graph (Fig. 7) with subsequent analytical support.

It is obvious from Fig. 7 that the noise intensity J of steels and alloys in the interval $o - \underset{\vee}{f}$ does not practically depend on f and is a random value. For this interval of frequencies, the equation has the form of a line that is parallel to the f axis.

The noise intensity J in the interval $\underset{\vee}{f} - \hat{f}$ is an exponential function of the form:

$$J(f) = J_0\left(1 - \frac{1}{e^{\alpha \cdot f}}\right), \text{dB}. \tag{1}$$

However, as studying function (1) shows, it is rather inconvenient and incorrect, therefore, there is offered an exponential function of the form:

$$J(f) = \alpha \cdot e^{\beta \cdot f}, \tag{2}$$

where α and β are statistical parameters determined in the laboratory.

For $\underset{\vee}{f}$ there is:

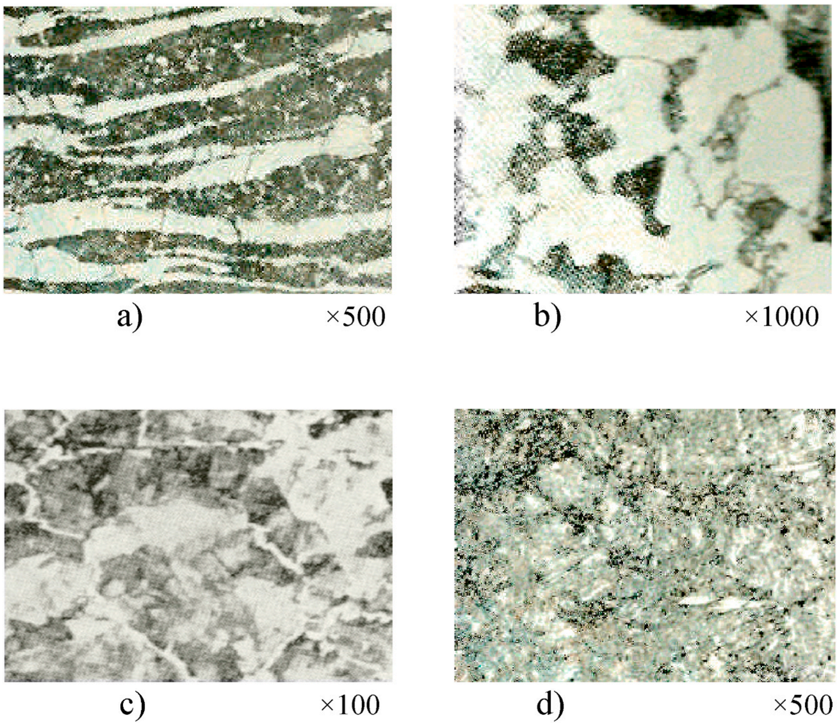

Fig. 6. Microstructure of the FK-2P alloy after forging (a), normalization (b), annealing (c), and hardening (d).

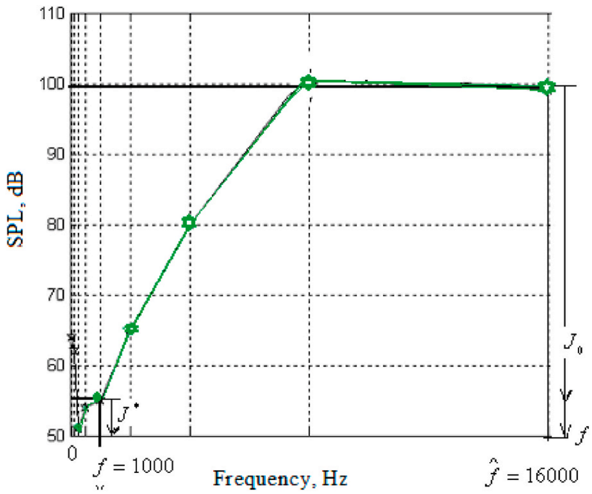

Fig. 7. Graph of dependence $J(f)$.

$$J\left(\check{f}\right) = \alpha \cdot e^{\beta \cdot \check{f}}, \tag{3a}$$

and for $\hat{f}$:

$$J\left(\hat{f}\right) = \alpha \cdot e^{\beta \hat{f}}. \tag{3b}$$

Let's divide the second equation by the first one; then:

$$\frac{J_0}{J^*} = e^{\beta\left(\hat{f} - \check{f}\right)}. \tag{4}$$

From (4) there is obtained:

$$\beta = \frac{1}{\hat{f} - \check{f}} \ln \frac{J_0}{J^*} \tag{5}$$

and then:

$$\alpha_{1,1} = \frac{J^*}{e^{\beta \cdot \check{f}}}; \tag{6}$$

$$\alpha_{1,2} = \frac{J_0}{e^{\beta \cdot \hat{f}}}.$$

At this the necessary condition is:

$$\alpha_{1,1} = \alpha_{1,2.} \tag{7}$$

Let's substitute β into (6), then:

$$\alpha_{1,1} = \frac{J^*}{\exp\left(\frac{1}{\hat{f} - \check{f}} \ln \frac{J_0}{J^*}\right)\check{f}}; \tag{8}$$

$$\alpha_{1,2} = \frac{J_0}{\exp\left(\frac{1}{\hat{f} - \check{f}} \ln \frac{J_0}{J^*}\right)\hat{f}}. \tag{9}$$

Let us consider the acoustic characteristics of sound emission J of cast structural steels after normalization in the frequency range $f = 1000–16000$ Hz. For example, for steel 30HGSA, the initial data are taken from the graph in Fig. 3:

$$\check{f} = 1 \cdot 10^3 Гц;\ \hat{f} = 16 \cdot 10^3 Гц.$$

$$J^* = 60 дБ;\ J_0 = 107 дБ.$$

According to formula (5) there is determined the parameter β: $\beta = \frac{1}{(16-1) \cdot 10^3} \ln \frac{107}{60} = 0,385 \cdot 10^{-4}$.

According to formulas (8) and (9) there is found the parameter α:

$$\alpha_{1,1} = \frac{60}{e^{0,385 \cdot 10^{-4} \cdot 10^3}} = 57,7;$$

$$\alpha_{1,2} = \frac{107}{e^{0,385 \cdot 10^{-4} \cdot 16 \cdot 10^3}} = 57,8.$$

The mean value is α = 57.75. So, the equation of the noise intensity for steel 30HGSA has the form:

$$J(f) = 57,75 e^{0,385 \cdot 10^{-4} \cdot f} \text{ dB} \tag{10}$$

Similar equations can be obtained for all the types of cast steels after various types of heat treatment. Thus, there is obtained the regularity $J(f)$ for the same 30HGSA steel after annealing:

$$\check{f} = 1 \cdot 10^3 Гц; \hat{f} = 16 \cdot 10^3 Гц.$$

$$J^* = 60 дБ; J_0 = 90 дБ.$$

Let's determine the β parameter: $\beta = \frac{1}{(16-1) \cdot 10^3} \ln \frac{90}{60} = 0,253 \cdot 10^{-4}$.

Then let's determine the α parameter:

$$\alpha_{1,1} = \frac{60}{e^{0,253 \cdot 10^{-4} \cdot 10^3}} = 58,5;$$

$$\alpha_{1,2} = \frac{90}{e^{0,253 \cdot 10^{-4} \cdot 16 \cdot 10^3}} = 60.$$

The mean value is α = 59.5. So, the required equation will have the form:

$$J(f) = 59,5 \cdot e^{0,253 \cdot 10^{-4} \cdot f}. \tag{11}$$

Comparing equations (10) and (11), there can be concluded that the noise emission indices of 30HGSA steel after annealing over the entire observation interval $\{10^{-3} \div 16 \cdot 10^{3}\}$ are significantly reduced.

Steel samples have been studied in a wide frequency range of 63–16000 Hz. For convenience of the analysis, the frequency range *f* is divided into two subsets.

1. $\{0 = f \leq 1000$ Hz $\}$, Hz;
2. $\{1000 = f \leq 16\ 10^{3}\}$, Hz.

Analyzing the results of numerous laboratory tests of prototype steels for drill rods and drill bit bodies, there can be concluded the following.

1. The noise characteristic *J* in dBA in the first interval $\{0 < f \leq 10^{3}\}$ does not depend on *f* but is a random variable characterized by known parameters.
2. During impact, the noise intensity characteristic *J* for test samples in the range of $\{10^{3} \leq f \leq 16 \cdot 10^{3}\}$ for any types of steels is subject to the exponential law with parameters characteristic of each type of steels and alloys.

5. Conclusions

Thus, in this article, the sound emission of alloys used for manufacturing perforator parts (drill rods and bit bodies) has been studied and the effect of heat treatment on the acoustic and damping properties of alloys has been evaluated. It has been found that the FK-2P alloy containing chromium (1.18%), silicon (0.88%), manganese (0.72%), nickel (3.75%), cerium (0 0.15%) with the carbon content of 0.48% (the rest is iron) possesses the best damping characteristics. The sound emission of this alloy after hot forging and normalization is 97 dB A, after annealing it is 95 dB A, after hardening it is 91 dB A.

After heat treatment the developed FK-2P steel takes on the ferrite-pearlite structure. This structure is characterized by an increased dislocation density, which makes it possible to increase the damping properties of the developed steel sample, reduces the noise level of the drill rod and the body of the perforator bit by 10–12 dB A, and helps to extend the service life of the equipment and to improve the working conditions in production shops.

The article establishes the regularities of noise intensity at different frequency intervals for standard and developed alloys. During the interaction (impact) of metal parts of mining machines, perforators, etc., the noise intensity *J* in the frequency range *f* up to 1000 Hz is a random variable and, in the frequency range from 10^{3} to $16 \cdot 10^{3}$ Hz, it strictly obeys the exponential law with parameters characteristic of each type of steel and alloys.

Author contribution statement

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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