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Impact noise reduction due to the use of steels with enhanced dissipative properties in the manufacture of mining equipment parts

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Abstract

Purpose. Research aims to study the influence of alloying elements on the properties of steels contributing to the increased sound energy dissipation and reduced acoustic emission in order to develop alloys for the manufacture of mining equipment parts operating in impact mode (drill string and drill bit housing.

Methods. Six alloys were developed during the research based on standard steels. Samples were melted in LPZ-1-67 high-frequency induction furnace at a melting temperature of 1700°C. All the samples were made in the form of 50×50×5 mm plates. KazNTU-2017 setup was used to study the impact noise level. The sound signal was calibrated using a ZG-10 generator. The results were corrected for atmospheric pressure using a PF-101 piston telephone. The temperature and humidity in the laboratory were maintained at a constant level. Acoustic measurements were made five times, with subsequent averaging of the results.

Findings. The developed alloys No. 4 and No. 6 have increased dissipative characteristics, which allows them to be classified as “quiet” steels. This is due to the increased graphite and ferrite content in their structure, which promotes effective absorption of sound energy. Alloy No. 3 has medium dissipative properties due to the presence of residual cementite in the structure.

Originality. Alloys No. 3, 4 and 6 have been found to have a damping logarithmic decrement (δ) of 2 times higher, relative scattering (ψ) of 3 times higher, and internal friction (Q^{-1}) also 3 times higher than that of standard steel grades used in mining machine parts.

Practical implications. The developed alloys No.3, No.4 and No.6 are recommended to be used in the manufacture of mining equipment parts. Their increased dissipative properties reduce the noise level of drill string and drill bit housing by 10-12 dBA, help increase the service life of units, as well as improve the working conditions of workers in the mining industry.

Keywords: *mining equipment, steel, alloy, sound level, noise intensity, attenuation velocity, internal friction*

1. Introduction

The mining industry is the basis of industrial development and plays a crucial role in providing the domestic and global economy with mineral resources [1], [2]. Ores of ferrous and non-ferrous metals, coal, non-metallic minerals and construction materials, mined by both open-pit and underground methods, are the raw material base for metallurgical, chemical, construction, energy and other industries. Increased demand for natural resources, as well as the development of infrastructure projects increase the pressure on the mining sector, stimulating the implementation of new technological solutions that ensure sustainability and safety of production processes [3]. This transition is supported not only by corporate initiatives but also by government strategies aimed at stimulating investment activity and industrial modernization [4], [5]. In particular, modern mining companies increasingly rely on knowledge-sharing practices and organizational innovation while addressing workforce challenges and skills gaps in STEM professions [6], [7].

At the same time, mining remains one of the most traumatic and technically complex industries. This is especially true for underground mining operations, where adverse mining-geological conditions, high degree of mechanization, limited space and presence of dangerous factors require strict compliance with occupational safety and health standards [8], [9]. In such conditions, ensuring the reliable operation of power supply systems becomes a vital safety factor. In particular, methods for assessing the insulation quality and parameters of asymmetric electrical networks up to 1000 V, as proposed by Utegulov et al. [10], [11], provide valuable tools for monitoring and preventing faults in mining enterprises, thereby reducing the risk of accidents caused by electrical failures. Underground, there is a constant threat of methane and other flammable gases accumulating, which creates a high risk of explosions and poses a serious danger to the life and health of workers [12]-[14]. In addition to explosion hazards, miners are exposed to a range of harmful production factors that have a chronic impact on the body on a daily basis. These

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factors include increased dustiness, vibrations, unstable microclimate and, especially, industrial noise [15], [16].

One of the most common and harmful factors accompanying the operation of mining equipment is noise pollution [17]. Modern underground mining enterprises are equipped with high-performance machines and mechanisms of impact and vibration action (drilling rigs, jackhammers, perforators, shearers, etc.), which are powerful sources of acoustic vibrations. Particularly harmful to the human body are impulse and impact noises, the level of which can reach 120-130 dBA.

Surveys of noise sources in the mining industry show that workplaces are dominated by mid- to high-frequency noise, which is 85-100 dB and often reaches 110-120 dB [18]-[20]. Pathological changes in workers are most often caused by the influence of high-frequency range sound (3000-6000 Hz). Long-term exposure to sound levels above normal levels can lead to poor health [21]-[23].

According to a World Health Organization report, occupational noise causes 16% of hearing loss in adults [24]. Exposure to noise causes occupational hearing loss that affects a person's quality of life [25]. The worker becomes anxious, resistance to stress decreases, and adaptation mechanisms are disturbed. Dullness of hearing can be a trigger for cardiovascular and nervous system diseases. Brodie A.J. Lawson et al. in [26] note that hearing loss can be a trigger for the development of diseases of the cardiovascular and nervous system.

The challenge of noise control in underground facilities is the limited use of traditional personal protective equipment and sound insulation. Therefore, the actual scientific-technical task is to reduce noise at the source of its occurrence by means of constructive solutions and the use of new materials with improved damping and dissipative characteristics. The development and implementation of such materials for the production of impact-loaded mining equipment parts is a promising direction that contributes to improving working conditions, reducing occupational risks and increasing the overall reliability of equipment. In this regard, special attention is paid to protective coatings and composite materials capable of enhancing wear resistance and simultaneously providing noise damping. For example, the formation of tripolyphosphate coatings on steel substrates has shown promising anticorrosion properties and structural stability under load [27]. In addition, recent studies on nitride and oxynitride coatings have demonstrated their effectiveness in protecting steel surfaces from high-temperature embrittlement and oxidation, while contributing to longer service life under harsh conditions [28]. Coatings with nanostructured ceramic-metallic layers also show good damping properties, which makes them suitable for use in critical components of mining equipment subjected to vibrational and acoustic loading [29].

Stucken et al. in [30] and Le et al. in [31], when studying the health condition of workers at a machine-building enterprise under noise conditions of 70-115 dBA, have revealed central nervous system disorders at low noise intensity. Scientists have found that with 10 years of work experience at noise level of 90-95dBA, workers experience a temporary or permanent shift in hearing threshold. Skogstad et al. [32] note that with a 13 dB increase in noise level, the frequency of functional nervous system disorders increases by 2 times, cardiovascular disorders by 3 times (in people associated with hard work), which can lead to workplace accidents. Degan et al. [33] investigate the impact of vibration on the health of workers in the mining industry and note its adverse effect on the musculoskeletal system of miners. Vibration sources are also sources of increased noise levels.

Reducing noise in the workplace to sanitary standards provides both social-environmental and economic effects on occupational safety [34], [35]. Therefore, solving the problem of industrial noise, in general, and impact noise, in particular, is an urgent task today.

The primary source of impulse impact noise at mines is industrial equipment, such as perforators, pneumatic and hydraulic drill hammers, percussion-rotary drilling machines with cutter bits, excavators, drill strings, gears, ratchets, levers, pulleys and other elements. Perforators, in particular, rank among the top noise levels in the mining industry. Pneumatic perforators, intended for drilling boreholes and wells in drilling-blasting operations, have a very high noise level of up to 120 dB. The use of solid drill strings increases productivity due to lower impact impulse losses, but generates noise intensity up to 120-130 dB[23]. Noise from mining equipment cannot be reduced by using sound-absorbing or sound-insulating materials, as well as by using personal hearing protection equipment. Therefore, the problem of reducing the noise of mining equipment, especially in underground mining, remains very difficult, and the research into sources of industrial noise for the development of technical solutions and improvement of technological equipment is extremely urgent.

Conventional noise reduction methods are not effective enough due to cluttering of working areas (sound insulation, sound absorption), masking of warning signals (use of personal hearing protection equipment), inefficiency, fire hazard, additional dustiness at the workplace (sound absorption). Reducing noise at the source of its occurrence – replacing impact processes with non-impact processes, replacing gear transmissions with V-belt gears, using non-metallic materials instead of metallic materials, etc., are effective ways to suppress industrial noise. However, on technological criteria, these methods are often irrational.

The most rational method of noise control is to reduce noise at the source of its occurrence, which can be achieved by using materials with enhanced dissipative properties [36], [37]. In this case, the most effective is the use of high-damping alloys with the ability to absorb the energy of sound vibrations in the structure itself, depending on such factors as the ratio of structure components, the type of technological processing, etc. For example, Luo et al. [38] developed low-carbon steel with 2% Nb content without adding Ni, Cr and W, which resulted in increased steel strength at high temperatures. In their publication, Girish et al. [39] presented the results of studies on the vibration damping capacity of annealed high-chromium (16%) ferromagnetic steel. Scientists have found that the damping capacity of the alloy increases after annealing.

Sun and Qiu in their research work [40] showed that the addition of 2 wt.% TiAl to 316L stainless steel moderately improved the yield strength by 0.2% and significantly increased the tensile strength due to the ground grain structure and massive γ-TiAl nanoparticle. Yan et al. [41] found that the addition of Zr element to Fe-Cr-based alloys improves the impact toughness while maintaining damping capacity.

Thus, the influence of chemical composition of alloys on damping properties leads to the assumption that it is possible to develop alloy steel compositions with high damping properties.

This paper presents the results of experimental tests of damping and dissipative characteristics of six newly developed steel alloys for producing perforator parts operating in the mode of collision (drill string and drill bit housing). The new steels are alloyed with silicon, manganese, chromium, sulphur and phosphorus. The authors of the paper conduct a comparative analysis of acoustic characteristics of standard and developed steels. The research purpose is to study the influence of alloying elements on steel properties that increase the dissipation of sound energy with a subsequent decrease in acoustic emission. Increased dissipative properties of steels reduce production noise at the source of its occurrence.

2. Materials and methods

For this research, 6 alloys alloyed with silicon, manganese, chromium, sulphur and phosphorus have been developed on the basis of standard free-cutting steels.

Hypoeutectoid alloys with carbon content from 0.15 to 0.50% were chosen as the object of research. These are carbon structural steels, characterized by rather high strength and technological properties. The content of alloying elements was determined by studying the Fe-C, Fe-Si, Fe-Cr, Fe-Mn, Fe-P and Fe-S diagrams. The content of alloying elements varied in the following ranges: manganese from 0.7 to 1.7%, chromium from 0.6 to 1.2%, sulphur from 0.18 to 0.4%, phosphorus from 0.14 to 0.4% and silicon from 0.30 to 0.37%, the rest was iron. The choice of alloying elements is conditioned by the fact that their content in free-cutting steels is recommended according to GOSTs of corresponding grades.

Silicon is an element that is constantly present in steels, which influences the composition and nature of non-metallic inclusions. Silicon is an effective graphitizator for steel. The presence of graphite increases the irreversible scattering of sound-vibration energy in steels. Silicon increases the yield strength, reduces the toughness of steel, and when its content is over 1%, increases the cold brittleness threshold. Manganese content in steel alloys can increase the strength in hot-rolled products while reducing their hot-brlttleness. Manganese is often used instead of nickel to increase the yield strength of a steel alloy. When adding manganese to the alloy, the damping properties of steel are markedly improved. Manganese and silicon added to steel to deoxidize the alloy structure. The presence of chromium in the alloy contributes to a uniform increase in the steel hardness. When steel is alloyed with chromium, the hardenability of the material increases. The widespread use of chromium in structural alloys is due to its good solubility in ferrite and cementite, which leads to improved mechanical properties of steel.

The smelting of experimental alloys was carried out in an LPZ-1-67 high-frequency induction furnace at a melting temperature of t = 1700°C, and the furnace power was 70 kW. A graphite crucible was used. The smelted metal was cast into 210×210×115 mm moulds. The ingots were annealed. Annealing was conducted according to the following regime: heating to 920-970°C, holding time 0.5 hours, slow cooling. Samples for acoustic performance tests were cut from forged strips. The surfaces of the plates were ground to a grade 5 finish. Dimensional deviations did not exceed 0.1 mm. All the test samples were made in the form of a 50×50×5 mm plate.

The following steels were adopted as standard:

– carbon sulphur (A12, A20, A30, A35 and A40G);

– carbon lead-containing (A11, AC14 and AC40);

– carbon sulphur-manganese and lead-containing (AC35G2 and AC45G2);

– carbon and chrome-sulphur-selenous (A35E, A45E, A40CE).

Mechanical and chemical characteristics of standard and developed alloys are presented in Tables 1 and 2 [42]. According to mechanical properties (Table 1), it can be seen that the standard steels A12, A20, A30, A35 and A40G (hot-rolled by type of processing) have the following parameters.

Table 1. Mechanical properties of standard and developed steels

Alloy grade	Temporary tear resistance, σ_t, MPa	Yield strength, σ_m, MPa	Relative elongation at rupture, δ_5, %	Relative contraction, ψ_c, %	Hardness (HB), (no more)	
	No more				Without heat treatment	Annealed
Standard steels						
A12	420		22	34	160	
A20	460		20	30	168	
A30	520		15	25	185	
A35	510		15	23	201	
A40G	600		14	20	207	
A11	410		19		205	
AC40	580	340	19		217	187
AC14	420		20		170	
AC35G2	740	590	14		229	217
AC45G2	640	440	6			229
A35E	540	320	20		187	
A45E	610	360	16		241	197
A40XE	1000	800	10			217
Alloys developed						
No. 1	430	340	21	31	180	145
No. 2	440	310	22	28	175	141
No. 3	510	340	20	30	164	140
No. 4	550	320	19	29	181	165
No. 5	580	360	15	22	222	195
No. 6	640	380	16	27	220	190

Table 2. Chemical composition of the studied alloys

Alloy grade	Content of elements, %										
	C	Si	Mn	Pb	Ni	Cr	Se	Cu	S	P	Fe
Standard steels											
A12	0.16	0.35	1.00						0.20	0.15	rest
A20	0.24	0.35	1.00						0.15	0.06	-//-
A30	0.35	0.35	1.00						0.15	0.06	-//-
A35	0.40	0.35	1.00						0.15	0.06	-//-
A40G	0.45	0.35	1.55						0.30	0.05	-//-
A11	0.15	0.10	1.20	0.30					0.25	0.10	-//-
AC40	0.17	0.12	1.30	0.30					0.20	0.10	-//-
AC14	0.48	0.10	1.65	0.35					0.35	0.04	-//-
AC35G2	0.45	0.37	0.80	0.30	0.25	0.25			0.04	0.04	-//-
AC45G2	0.39	0.37	1.65	0.30	0.25	0.25			0.13	0.04	-//-
A35E	0.40		0.8		0.12	0.25	0.1	0.30	0.12	0.04	-//-
A45E	0.40		0.8		0.12	0.25	0.1	0.30	0.12	0.04	-//-
A40XE	0.44		0.8		0.30	1.10	0.1	0.30	0.12	0.35	-//-
Developed steels											
No. 1	0.25	0.30	0.8			1.0			0.18	0.14	-//-
No. 2	0.30	0.30	1.0			0.6			0.4	0.20	-//-
No. 3	0.45	0.35	1.4			1.0			0.35	0.35	-//-
No. 4	0.50	0.37	1.7			1.2			0.4	0.4	-//-
No. 5	0.30	0.30	0.7			0.7			0.25	0.25	-//-
No. 6	0.45	0.35	1.4			0.9			0.30	0.40	-//-

Hardness (HB) without heat treatment from 160 to 207, relative contraction of cross-sectional area at rupture (ψ_c, %) – 20-34, temporary tear resistance ($\delta_в$,) – 420-600 MPa, relative elongation at rupture (δ_5) – 14-22%. The chemical composition of free-cutting steels (A12, A20, A30, A35 and A40G) is characterized by the content of carbon – from 0.16% to 0.45%, silicon – 0.35%, manganese – from 1.0 to 1.55%, sulphur – from 0.15 to 0.30%, phosphorus – from 0.05 to 0.15%, the rest is iron (Table 2).

Mechanical properties of carbon lead-containing and sulphur-manganese lead-containing steels of A11, AC14, AC40, AC35G2 and AC45G2 grades show that A11, AC40 and AC14 (without heat treatment) have the following characteristics: HB – 170-217, δ_5 –19-20%, δ_t – 410-580 MPa, while AC352 and AC45G2 (annealed) have HB-217 and 229, δ_5 – 14 and 6%, δ_t – 740 and 640 MPa, respectively. The chemical composition of steel A11, AC14, AC35G2, AC45G2 and AC40 is characterized as follows: carbon content ranges from 0.15% to 0.48%, silicon – 0.1-0.37%, manganese – 0.8-1.65%, nickel and chromium – 0.25% (AC45G2 and AC35G2), lead – 0.30-0.35%, sulphur – 0.04-0.35%, phosphorus – 0.04-0.10%, the rest is iron.

Carbon sulphur-selenous steels A35E and A45E (without heat treatment) have the following mechanical characteristics: HB-187 and 241, δ_5 – 16 and 20%, δ_t – 540 and 610 MPa, ultimate compressive strength (δ_y) – 320 and 360 MPa, while A40XE steel grade (annealed) – HB-217, δ_5 –10%, δ_t – 1000 MPa, δ_y – 800 MPa. The chemical composition of the above steels is as follows: carbon – 0.40-0.44%, chromium – 0.25-1.1%, manganese – 0.8%, nickel – 0.12-0.30%, copper – 0.30%, selenium – 0.10%, sulphur – 0.12%, phosphorus – 0.04-0.35%, the rest is iron.

Table 1 shows that the developed alloys No. 1-No. 6 are not inferior to standard alloys in terms of mechanical properties and have the following parameters: HB without heat treatment is in the range of 164-222, annealed 140-190, δ_5 – 15-22%, δ_t – 430-640 MPa, δ_y – 310-380 MPa, ψ_c – 22-31%. The chemical composition of the developed steels (No. 1-No. 6) contains carbon – 0.25-0.5%, silicon – 0.30-0.37%, manganese – 0.7-1.4%, chromium – 0.6-1.2%, sulphur – 0.18-0.4%, phosphorus – 0.14-0.4%, the rest is iron.

To study the noise of collision of standard steels and developed alloys, the KazNTU-2017 setup is used (Fig. 1) [37].

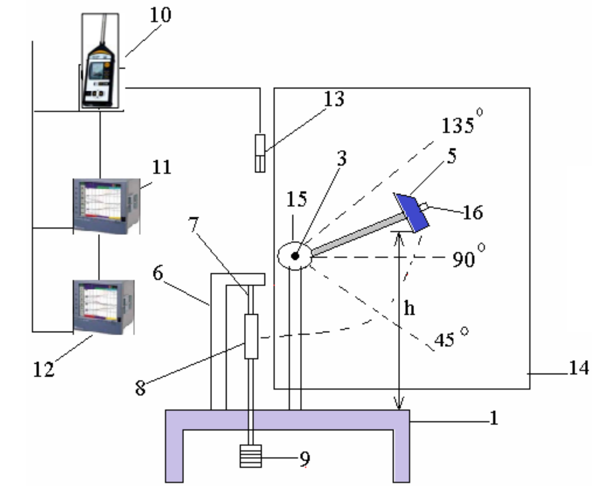

Figure 1. KazNTU-2017 setup for studying noise in the collision of flat metal samples: 1 – base; 2 – post; 3 – axis; 4 – impactor rod; 5 – impactor; 6 – sample mounting bracket; 7 – sample mounting threads; 8 – sample; 9 – load; 10 – sound level meter; 11 – oscilloscope; 12 – self-recording meter; 13 – microphone; 14 – impactor deflection scale; 15 – retainer; 16 – nut

The device has an impactor *5* in the form of a hammer weighing 218 g. The impactor is attached to the rod *4* by means of a nut *16*. The hammer can perform impacts with varying force. When performing experimental tests, the impactor was deflected at different angles from the equilibrium position to a certain height h and angle, which were determined using scale *14*. The impactor was deflected at 45º (h_1 = 10 cm), 90º (h_2 = 17 cm) and 135º (h_3 = 25 cm). When the impactor was released, it collided with the tested steel sample under its own weight. After collision, the impactor was stopped by the retainer *15* to prevent a repeated impact. The collision noise level was measured by an accurate Octave-101A impulse sound level meter *10*, the attenuation curve of the impact process was recorded by an oscillator *11* and a self-recording meter *12*. Sound pressure levels (SPL) were examined in octave frequency bands in the range of 63-16000 Hz. Sound level – on the "A" scale. The sound level meter indicator allows recording sound pressure levels from 30 to 130 dB with an accuracy of 0.5 dB. Using a PCS-500 storage oscilloscope connected to a personal computer, the sound impulse from the collision of the test sample with a hammer was recorded. In this case, the time interval of the oscilloscope screen is taken as 2 ms.

The ZG-10 sound generator was used to calibrate the sound signal measurements. Correction for signal variation depending on atmospheric pressure was made using a PF-101 pistonphone. The air temperature and humidity in the laboratory were maintained at a constant level. Acoustic measurements were taken as the average value of five measurements.

To identify steel samples with dissipative properties, standard free-cutting and developed metallic materials in the form of alloys were tested. The sound impulse from the collision of the test sample with the hammer was recorded with a sound level meter and recorded with a PCS-500 storage oscilloscope. Damping and dissipative characteristics were determined from the signal recorded on the computer monitor. Logarithmic decrement and sound attenuation velocity were determined while recording the collision sound impulse, and characteristics such as relative scattering and internal friction were determined by calculation.

To determine the natural logarithm of two consecutive peak sound level values (logarithmic decrement), the following Formula was used:

$$\delta = \frac{1}{n}\ln\frac{A_0}{A_n}, \quad (1)$$

where:

A_0 – initial, maximum amplitude of the sound impulse;

A_n – final, minimum amplitude of the sound impulse;

n – the number of impulses on the oscilloscope screen.

The sound attenuation velocity was determined by the Formula:

$$V = \frac{L_1 - L_2}{\tau}, \quad (2)$$

where:

V – the sound attenuation velocity, dB/sec;

L_1 – maximum sound level, dB;

L_2 – sound level over time τ, dB;

τ – time, s.

The attenuation velocity of the oscillatory process (relative scattering) was determined by the Formula:

$$\psi = 2\cdot\delta. \quad (3)$$

The ability of a solid body to irreversibly dissipate energy is characterized by internal friction. The manifestation of internal friction is the attenuation of free oscillations of a solid body. Internal friction is measured at high and low amplitudes. The amplitude function in the large amplitude range is internal friction, called amplitude-dependent internal friction. This characteristic is of practical importance for manufacturing and is referred to as material damping capacity and microplate internal friction. Internal friction was determined by the Formula:

$$Q^{-1} = \frac{\delta}{\pi} = \frac{\psi}{2\pi}. \quad (4)$$

Values obtained were used for comparative analysis of steel and alloy samples in order to identify the most promising materials with high damping properties for use in structures exposed to vibration loads.

3. Results and discussion

3.1. Study on damping and dissipative properties of developed steels

Damping characteristics of the studied alloys, both standard free-cutting steels and newly developed alloys obtained during the experiment are given in Table 3. From the data obtained, it can be seen that the sound level of the standard free-cutting steels ranges from 80 to 86 dB, whereas that of the developed alloys ranges from 74 to 84 dBA. The lowest sound level values among standard steels are observed for A20 and A35 grades of alloys – 80 dBA. The values characterizing damping properties of these steel grades are almost identical: logarithmic decrements are equal ($\delta = 0.0027$), relative scattering $\psi = 0.0043$ and 0.0044, respectively, internal friction $Q^{-1} = 0.00070$ and 0.00071, respectively.

Among the developed steels, the lowest sound level was found in alloy No. 4 – 74 dBA, which is 6 dBA less compared to steel grades A20 and A35. The damping properties of the studied alloy are higher than those of the compared free-cutting steels and are equal to: $\delta = 0.0043$; $\psi = 0.0086$; $Q^{-1} = 0.0021$.

The developed alloy No. 6 has a sound level of 75 dBA at $\delta = 0.0039$; $\psi = 0.0078$; $Q^{-1} = 0.0019$, that is, compared to steel grades A20 and A35 there is a decrease in the sound level by 5 dBA and increase in the values of dam-ping characteristics. Compared to grades A20 and A35, alloy No. 3 has a sound level 3 dBA lower and equal to 77 dBA with increased damping characteristics $\delta = 0.0036$; $\psi = 0.0072$; $Q^{-1} = 0.00115$.

Alloys No. 1, 2 and 5 have higher sound level values of 78 and 84 dBA compared to the other developed alloys. However, at the same time, compared to other standard free-cutting steels, the studied alloys have 2-8 dBA lower sound level values and higher damping characteristics.

To study the dependence of sound level on damping and dissipation characteristics (δ, ψ, Q^{-1}), the graphs shown in Figures 2-4 were plotted using the data in Table 3. The graph in Figure 2 shows that the sound level is dependent on the logarithmic decrement ($\delta\cdot10^{-3}$), namely, there is a decrease in the sound level with increasing numerical values of the logarithmic decrement. The left half of the graph is characterized by higher sound levels and lower logarithmic decrement values corresponding to standard free-cutting steels. Thus, steel grades AC14, A11, AC40, AC35G, AC45G2, A30, A11, A40G and A35E, A45E, A40XE with logarithmic decrement values ($\delta\cdot10^{-3}$) from 0.7 to 2.0 have an increased sound level of 86 dBA and 85 dBA, respectively. The right half of the graph shows a sharp decrease in sound level with increasing logarithmic decrement ($\delta\cdot10^{-3} > 2$), and in this part of the graph, there are mainly developed for this research steels and standard steels A20 and A35.

Table 3. Damping characteristics of the studied alloys

Alloy grade	A_0, mm	A_n, mm	n	δ	V	ψ	Q^{-1}	Sound level (L_A), dBA
Standard steels								
A12	28	21.0	47	0.0019	72.3	0.0022	0.00049	86
A20	30	15	43	0.0027	80.8	0.0043	0.00070	80
A30	33	12,5	51	0.0018	74.5	0.0037	0.00048	86
A35	30	10	48	0.0027	72	0.0044	0.00071	80
A40G	31	12	49	0.0020	76.3	0.0040	0.00064	86
A11	35	16	53	0.0008	70.6	0.0016	0.00025	86
AC40	30	18	50	0.0009	70.6	0.0018	0.00029	86
AC14	39	13	51	0.0007	70.6	0.0014	0.00022	86
AC35G2	39	24	46	0.0010	78.6	0.0020	0.00032	86
AC45G2	28	12	49	0.0011	70.6	0.0022	0.00035	86
A35E	40	12	48	0.0013	78.8	0.0025	0.00041	85
A45E	32	16	44	0.0015	80.6	0.0026	0.00042	85
A40XE	41	16	48	0.0017	78.3	0.0027	0.00043	85
Developed steels								
No. 1	48	18	32	0.0022	84.9	0.0041	0.00068	84
No. 2	37	23	41	0.0030	78.1	0.0046	0.00078	78
No. 3	35	10	51	0.0036	86.5	0.0072	0.00115	77
No. 4	41	25	45	0.0043	94.7	0.0086	0.0021	74
No. 5	24	11	48	0.0033	87.1	0.0047	0.00079	78
No. 6	35	18	30	0.0039	92.0	0.0078	0.0019	75

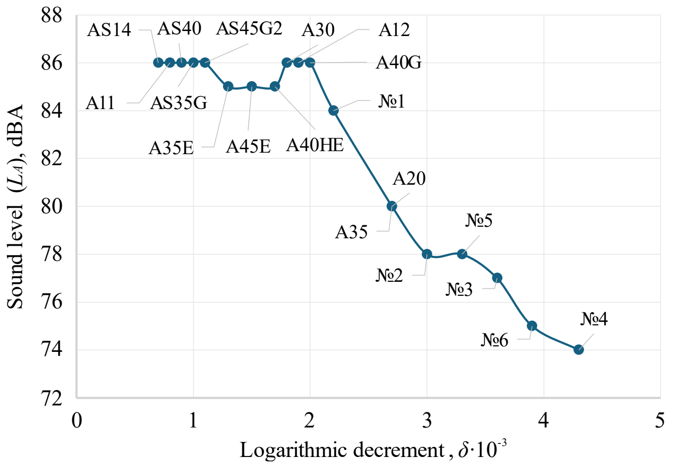

Figure 2. Graph of dependence of sound level on logarithmic decrement of free-cutting alloys

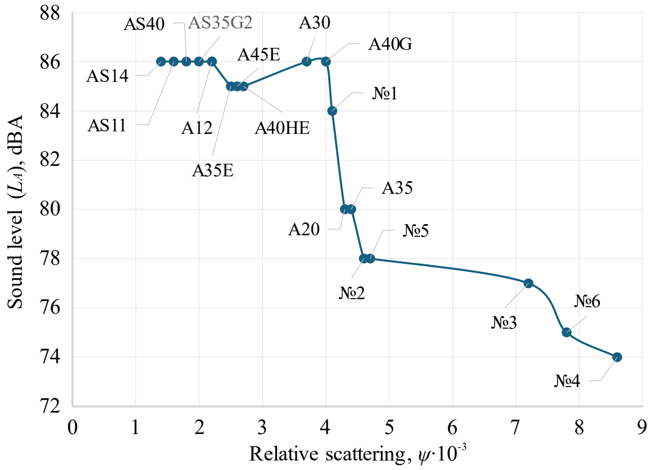

Figure 3. Dependency graph of the sound level on the relative scattering of free-cutting alloys

The maximum value of logarithmic decrement and minimum sound level are observed in developed alloy No. 4 ($\delta \cdot 10^{-3} = 4.3$; SL = 74 dBA), then in alloy No. 6 ($\delta \cdot 10^{-3} = 3.9$; SL = 75 dBA) and in alloy No. 3 ($\delta \cdot 10^{-3} = 3.6$; SL = 77 dBA). These alloys have a logarithmic decrement value almost twice as high as that of standard alloys.

Figure 3 shows a dependency graph of sound level on the relative scattering of free-cutting alloys ($\psi \cdot 10^{-3}$), indicating that there is a certain relationship between the parameters studied. The graph shows a decrease in sound level when increasing the value of relative scattering. In the left part of the graph, there are points corresponding to the data of standard steels. Standard steels AC14, A11, AC40, AC35G2, A12, A35E, A40XE, A30 and A40G with numerical relative scattering values ($\psi \cdot 10^{-3}$), ranging from 1.4 to 4.0, have an increased sound level of 85-86 dBA. The right part of the graph shows a sharp decrease in the sound level with increasing relative scattering value starting from $\psi \cdot 10^{-3} = 4$. The developed and standard steels A20 and A35 are located in this part of the graph.

The maximum relative scattering and minimum sound level are again observed in alloy No. 4 ($\psi \cdot 10^{-3} = 8.6$; 74 dBA), then in alloy No. 6 ($\psi \cdot 10^{-3} = 7.8$; SL = 75 dBA) and in alloy No. 3 ($\psi \cdot 10^{-3} = 7.2$; SL = 77 dBA).

These alloys have a relative scattering 3 times higher than known steel grades.

Figure 4 shows a dependency graph of sound level on internal friction, which shows that with the increase of internal friction value, the acoustic characteristics of metallic materials improve, that is, the sound level value decreases. A maximum sound level of 85-86 dBA is observed for standard steels, with internal friction values ($Q^{-1} \cdot 10^{-3}$) ranging from 0.22 to 0.64. A further increase in the value of this damping characteristic leads to a sharp decrease in the sound level. The graph shows that with increase in the internal friction value in alloys No. 3 ($Q^{-1} \cdot 10^{-3} = 1.15$), No. 6 ($Q^{-1} \cdot 10^{-3} = 1.9$), No. 4 ($Q^{-1} \cdot 10^{-3} = 2.1$), there is a decrease in sound level to 77, 75 and 74 dBA, respectively. These alloys have 3 times higher internal friction than standard alloys.

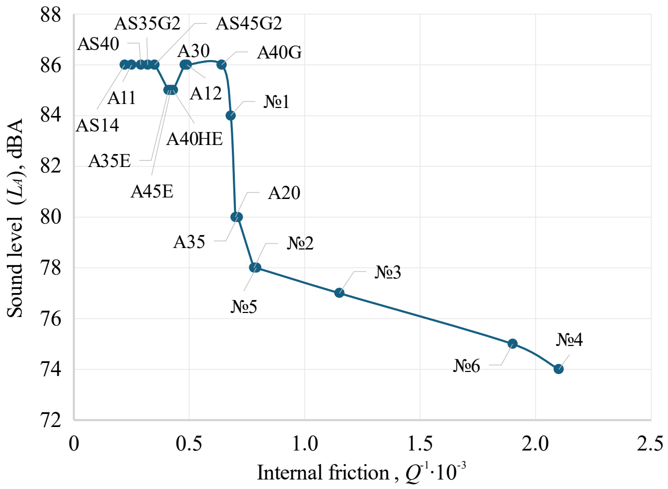

Figure 4. Sound level dependence on internal friction ($Q^{-1}\cdot10^{-3}$) of studied alloys

Thus, research on the dependence of sound level on the studied parameters (δ, ψ, Q^{-1}) indicates a decrease in sound emission during the collision of metallic materials (steels) with increasing numerical values of logarithmic decrement, relative scattering and internal friction.

Table 3 data contains information on the sound attenuation velocity during the collision of the studied alloys in the cast state for both standard and developed steels. Table 3 shows that the standard steels have lower sound attenuation velocity (70.6 to 80.8 dBA/s) compared to the developed alloys (78.1 to 94.7 dBA/s). Among the standard alloy series, the A45E and A20 grades have the highest sound attenuation velocities (80.6 and 80.8 dBA/s). At the same time, the A20 grade has a quite low sound level (80 dBA), while the A45E grade has a higher sound level of 85 dBA.

Experimental alloy No. 1 has the highest sound level (84 dBA) and low sound attenuation velocity (84.9 dBA/s) compared to other developed alloys No. 3, 4, 5 and 6. This indicates that the dissipative properties of the developed alloy No. 1 in the cast state are similar to the standard ones. Among the developed alloys, sample No. 2 in the cast state has the lowest sound attenuation velocity (78.1 dBA/s) and reduced sound level (78 dBA). The sample No. 5 is characterized by such sound level (78 dBA), but this sample has a sound attenuation velocity higher by 9 dBA/s (87.1 dBA/s) than sample No. 2. The maximum values of sound attenuation velocity among the studied steel samples are found in alloys No. 4, 6 and 3 (94.7; 92.0 and 86.5 dBA/s, respectively), while they have minimum sound levels (74, 75 and 77 dBA, respectively).

From the analysis of Table 3 and graphs in Figures 2-4, it can be seen that alloys No. 3, 4 and 6 have increased sound energy dissipation compared to the studied developed and standard free-cutting steels. The dissipative properties of an alloy can generally be influenced by its structure due to the specific characteristics of its microstructure. The relationship between dissipative properties and alloy structure is due to the internal structure of the material, which influences its ability to efficiently process and dissipate energy under various influences.

Examine the oscillograms of sound impulse attenuation from the collision of the impactor and samples of standard A35 and experimental samples of alloys No. 3, 4 and 6.

Figure 5 shows the oscillogram of sound impulse attenuation from the collision of the impactor with standard steel A35 (cast state), according to which the damping characteristics are determined: $\delta\cdot10^{-3} = 2.7$; $Q^{-1}\cdot10^{-3} = 0.71$; $\psi\cdot10^{-3} = 4.4$. These values are much higher than those of other standard steels studied, except for A20 grade steel, the properties of which are almost identical to those of A35 steel. Compared to newly developed steels, the damping characteristics of A35 steel are lower, except for alloy No. 1. The oscillogram of the tested sample of standard steel A35 shows that the pattern of the sound impulse distribution is uniformly decreasing. The initial sound level is 80 dB.

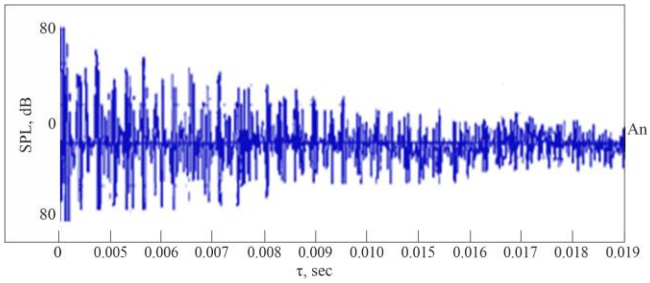

Figure 5. Oscillogram of the sound impulse attenuation from the collision of the impactor with standard free-cutting steel A35

The oscillogram of sound impulse attenuation from collision of the impactor with the experimental alloy No. 3 sample (cast state) is shown in Figure 6, according to which the damping and dissipative characteristics of the sample are determined: $\delta\cdot10^{-3} = 3.6$; $\psi\cdot10^{-3} = 7.2$; $Q^{-1}\cdot10^{-3} = 1.15$. These values are much higher than those of other studied standard alloy steels and experimental samples, with the exception of alloys No. 4 and 6. Steel sample No. 3 has an initial sound level of 77 dBA, after half of the time interval the sound impulse is halved.

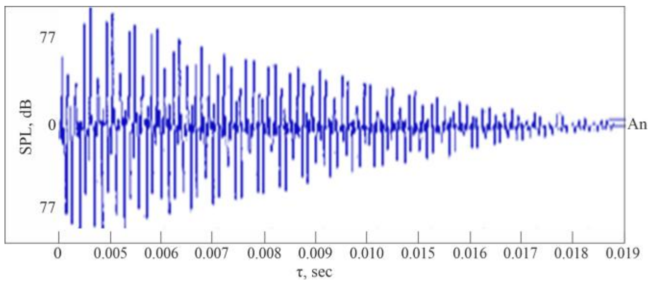

Figure 6. Oscillogram of the sound impulse attenuation from the collision of the impactor with the developed alloy No. 3

Figure 7 shows the oscillogram of sound impulse attenuation from the collision of the impactor with the developed sample No. 4 (cast state), according to which the damping and dissipative characteristics are determined, equal to the following values: $\delta\cdot10^{-3} = 4.3$; $\psi\cdot10^{-3} = 8.6$; $Q^{-1}\cdot10^{-3} = 2.1$. These values are the highest compared to other standard and experimental steel samples.

Figure 8 shows the oscillogram of sound impulse attenuation from the collision of the impactor with the developed alloy No. 6, according to which the damping and dissipative characteristics are determined, equal to the following values: $\delta\cdot10^{-3} = 3.9$; $\psi\cdot10^{-3} = 7.8$; $Q^{-1}\cdot10^{-3} = 1.9$.

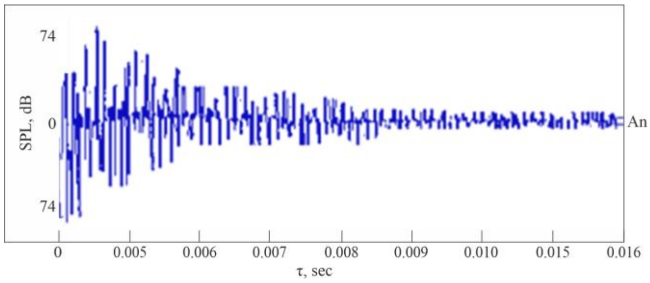

Figure 7. Oscillogram of the sound impulse attenuation from the collision of the impactor with the developed alloy No. 4

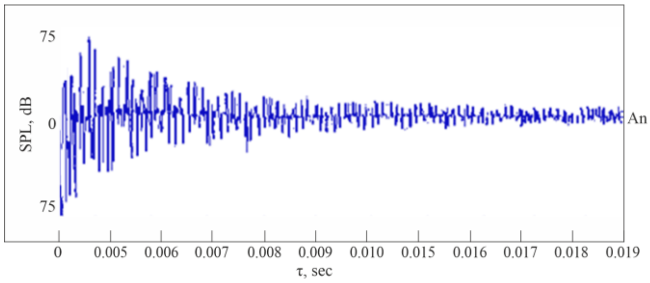

Figure 8. Oscillogram of the sound impulse attenuation from the collision of the impactor with the developed alloy No. 6

These values also exceed the values of other studied standard and experimental samples, except for alloy No. 4.

Oscillograms of dissipative alloys No. 4 and 6 on sound impulse attenuation show a rapid decrease in sound level, which on a large time interval remains within the range of 25-35 dBA. The initial sound levels are 74 and 75 dBA, respectively. This indicates that the sound wave dissipation pattern of samples No. 4 and 6 is higher than that of the standard sample A35.

In general, the oscillograms of sound impulse attenuation show that the experimental samples of alloys No. 3, 4 and 6 have higher values of sound attenuation velocity, logarithmic decrement, internal friction and relative scattering compared to other studied standard and developed steels.

3.2. Comparative analysis of acoustic characteristics of the studied steels

A comparative analysis has been performed of the dependence of the sound pressure level (SPL) on the geometric mean frequency of octave bands and the sound level of the studied standard/developed free-cutting alloys. Sound emission characteristics are compared between:

– developed alloy No. 3 and standard steels grades A40XE, A45E, A35E;

– developed alloy No. 4 and standard steel grades AC14, AC11, AC40, AC35G2 and AC45G2;

– developed alloy No. 6 and standard steel grades A12, A20, A30, A35.

Acoustic characteristics depending on frequency in octave bands of the developed alloy No. 3 and standard free-cutting steels of A35E, A45E, A40XE grades are presented in Table 4 and Figure 9, which show that alloy No. 3 at high frequencies (8000 and 16000 Hz) has SPL values 6-10 dB lower compared to standard samples. At low frequencies from 125 to 500 Hz, the SPL values of the developed alloy No. 3 are lower by 1-3 dB or have equal values.

Analysis of the microstructure of alloy No. 3 (Fig. 10) shows that this sample has a sufficiently large amount of graphite and ferrite in its composition, which increases the sound wave dissipation in the studied sample.

Table 4. Comparison of acoustic characteristics of developed alloy No. 3 with standard steels A40XE, A45E and A35E

Sample grade	Sound pressure level (dB), in octave bands with geometric mean frequencies, Hz								Sound level (L_A), dB
	125	250	500	1000	2000	4000	8000	16000	
No. 3	41	44	45	50	58	66	72	75	77
A40XE	40	45	46	54	61	67	78	82	85
A45E	41	47	48	56	63	68	80	86	85
A35E	41	47	48	56	63	68	81	85	85

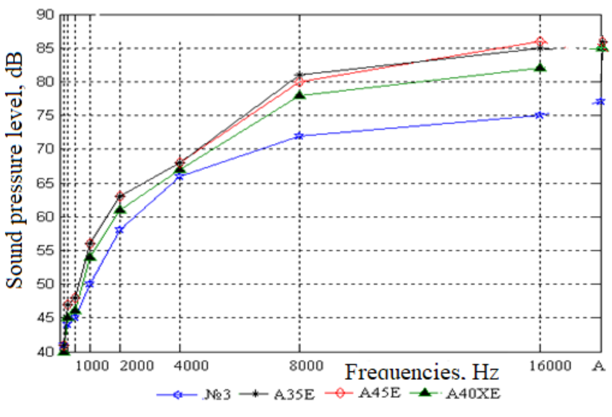

Figure 9. Comparison of the dependence of sound intensity on frequency of the developed alloy No. 3 and standard steels A45E, A35E and A40XE

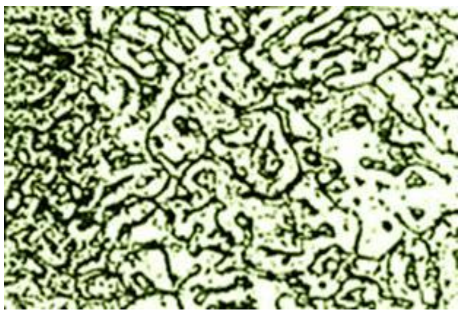

Figure 10. Microstructure of alloy No. 3 (1:300)

Table 5 and Figure 11 show the acoustic characteristics of the developed alloy No. 4 and standard steels AC14, A11, AC40, AC35G2 and AC45G2. Sound levels of standard free-cutting steels AC14, AC11, AC40, AC35G2 and AC45G2 are 86 dBA.

This in comparison with the sound level of developed alloy No. 4 is higher by 12 dBA, that is, the standard steels are significantly inferior in dissipative properties to the experimental alloy No. 4.

At the maximum frequency of 16000 Hz, the SPL of alloy No. 4 is 7-9 dB lower than that of the studied standard samples. At low frequency (125-500 Hz), the SPL values of the developed sample No. 4 and the known samples have a difference of up to 4 dB.

Table 5. Comparison of acoustic characteristics of developed alloy No. 4 and standard steels AC14, A11, AC40, AC35G2 and AC45G2

Alloy grade	Sound pressure level (dB), in octave bands with geometric mean frequencies, Hz								Sound level (L_A), dBA
	125	250	500	1000	2000	4000	8000	16000	
No. 4	40	45	44	51	59	65	75	79	74
AC14	41	45	48	59	69	75	82	88	86
A11	44	46	48	56	65	72	78	87	86
AC40	43	47	46	54	62	72	80	87	86
AC35G2	40	45	43	48	57	65	80	86	86
AC45G2	41	45	44	49	61	67	82	86	86

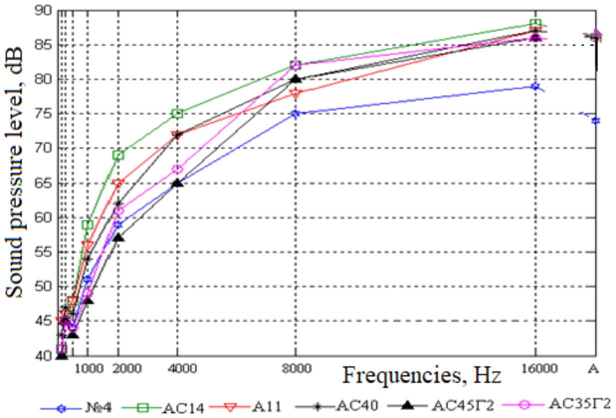

Figure 11. Comparison of the dependence of sound intensity on frequency of the developed alloy No. 4 and standard steels AC14, A11, AC40, AC35G2 and AC45G2

Reduction of sound emission in sample No. 4 is caused by high content of carbide-forming elements (carbon, silicon, manganese and chromium) in its structure and occurrence of coarse ferrite grains (Fig. 12).

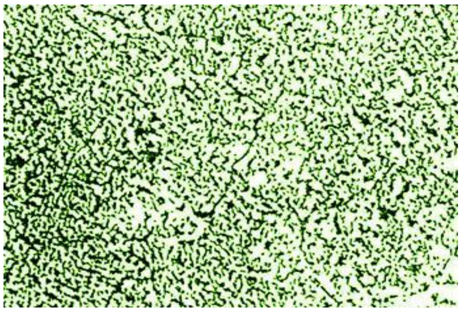

Figure 12. Microstructure of alloy No. 4 (1:200)

Acoustic characteristics of the developed alloy No. 6 and standard steels A12, A20, A30, A35, A40G are presented in Table 6 and Figure 13. Alloy No. 6 does not differ in its composition from standard free-cutting steels A12, A20, A30, A35, A40G. The SPL values of alloy No. 6 at all frequency levels have deviations by 1-7 dB in the direction of decrease and increase in comparison with standard steels.

A 5-11 dBA decrease in the sound level of sample No. 6, compared to the studied standard steel samples, is caused by the higher content of ferrite than perlite.

Table 6. Comparison of acoustic characteristics of developed alloy No. 6 and standard steels A12, A20, A30, A35, A40G

Sample grade	Sound pressure level (dB), in octave bands with geometric mean frequencies, Hz								Sound level (L_A), dBA
	125	250	500	1000	2000	4000	8000	16000	
No.6	41	45	46	55	59	65	83	86	75
A12	40	44	48	52	62	68	84	86	86
A20	41	49	46	47	57	67	78	84	80
A30	40	44	47	50	60	71	87	88	86
A35	41	42	46	47	58	66	76	86	80
A40G	41	44	48	52	61	69	80	87	86

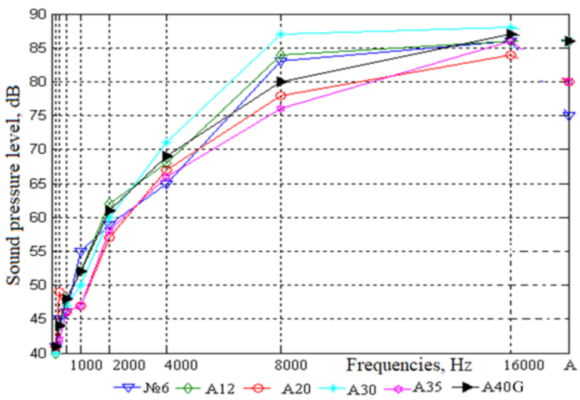

Figure 13. Comparison of the dependence of sound intensity on frequency of the developed alloy No. 6 and standard steels A12, A20, A30, A35, A40G

Ferrite is better in sound scattering compared to perlite. Perlite is weak in sound scattering due to its high cementite content, and therefore does not have a graphite structure that would help reduce sound emission (Fig. 14).

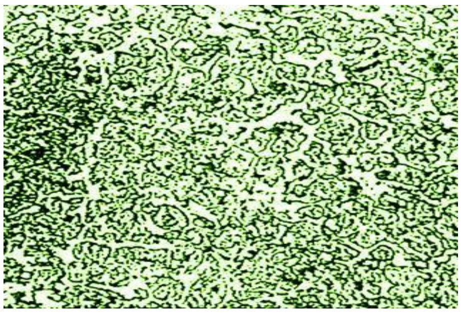

Figure 14. Microstructure of alloy No. 6 (1:200)

Table 7 contains acoustic characteristics of alloys No. 3, 4 and 6 for comparative analysis. According to the data in Table 7 and Figure 15, it is evident that at low frequencies of octave bands (125-500 Hz), the SPL values of alloys No. 3, 4 and 6 have insignificant deviations of 1-2 dB. The same is observed at 2000 and 4000 Hz, the deviations are less than 1 dB. At a frequency of 1000 Hz, $SPL_{No.3} = 50$ dB, and $SPL_{No.6} = 55$ dB, which shows a difference of 5 dB.

Table 7. Comparison of acoustic characteristics of developed alloys No. 3, 4 and 6

Alloy grade	Sound pressure level (dB), in octave bands with geometric mean frequencies, Hz								Sound level (L_A), dBA
	125	250	500	1000	2000	4000	8000	16000	
No. 3	41	44	45	50	58	66	72	75	77
No. 4	40	45	44	51	59	65	75	79	74
No. 6	41	45	46	55	59	65	83	86	75

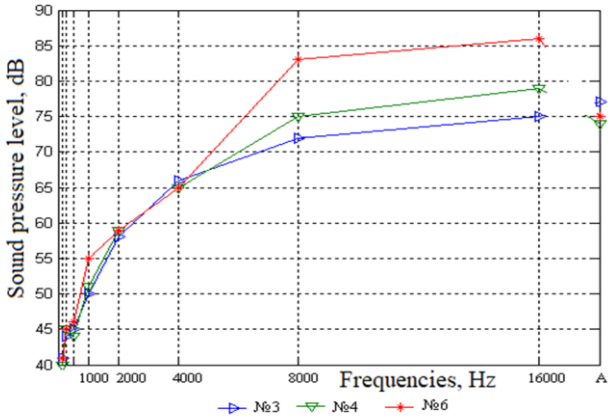

Figure 15. Comparison of the dependence of sound intensity on frequency of the developed alloys No. 3, 4 and 6

At the same time, the difference in SPL between alloys No. 3 and 4 is 1 dB.

At high frequencies of 8000 and 16000 Hz, there is a noticeable increase in the SPL of the studied samples, and the differences in these values are quite marked. At a frequency of 8000 Hz, the lowest SPL is for alloy No. 3 (72 dB) and the highest is for alloy No. 6 (83 dB). The same pattern is observed at a frequency of 16000 Hz: minimum SPL for alloy No. 3 (75 dB), maximum – for alloy No. 6 (86 dB).

Such distinctive acoustic characteristics are caused by the different sounds produced by the samples upon collision, where the cause is the structural state of alloys, which depends on their chemical composition. Among the developed alloys, samples No. 3, 4 and 6 belong to the low-noise alloys. The "quietest" alloy is No. 4, containing 0.50% carbon and combined alloying with silicon (0.37%), manganese (1.7%), chromium (1.2%) and an additional increased content of sulfur and phosphorus (0.4%). This chemical composition has reduced the sound level by 6-12 dBA compared to standard free-cutting steels. Maximum alloying with carbon and silicon (0.50 and 0.37%, respectively) contributed to the formation of graphite in the alloy structure, which provided an increase in the dissipative properties of the developed sample No. 4 (Fig. 12).

Thus, the optimum values of dissipative properties are recorded in samples No. 4 and 6, they are the "quietest" alloys compared to standard free-cutting and developed ones. Alloy No. 3 belongs to medium-dissipative alloys among all studied samples.

4. Conclusions

This paper presents the results of research on acoustic properties of standard and newly developed alloy samples. When studying the developed alloy samples, oscillograms of sound impulse attenuation from the collision of alloys were recorded using a PCS-500 oscilloscope to determine the damping and dissipative properties such as logarithmic decrement, relative scattering and internal friction of sound waves. Studies of the dependence of damping and dissipation characteristics of standard and developed alloys have shown that in alloys No. 3, 4 and 6, the damping logarithmic decrement (δ) is 2 times higher than in standard ones, and relative scattering (ψ) is 3 times higher from known steel grades, internal friction (Q^{-1}) is 3 times higher than in standard grades.

The results of the research on acoustic properties of the developed alloys and microstructure analysis led to the following conclusions:

– developed alloys No. 4 and 6 have increased dissipative characteristics, which allows them to be classified as "quiet" steels compared with standard free-cutting steels, since the structure contains more graphite and ferrite, which enhances the sound-absorbing properties;

– alloy No. 3 belongs to medium dissipative alloys in the developed series, that is, in addition to ferrite there are residual cementite content in the composition, which influences a slight decrease in dissipative properties compared to samples No. 4 and 6.

These alloys are recommended to be used for the manufacture of parts and components of mechanisms and equipment, namely, perforator parts operating in the mode of collision (drill string and drill bit housing). The enhanced dissipative properties of iron-carbon samples help to reduce the noise level and thus extend the service life of equipment, thereby improving the working conditions of miners.

Author contributions

Conceptualization: FB, GS; Data curation: FB, GS; Investigation: FB, GS, RO, KT, AN, AD, AK; Methodology: FB, GS, RO, AD; Project administration: FB, GS; Supervision: FB, GS; Validation: FB, GS, RO, AD; Writing – original draft: FB, GS, RO, KT, AN, AD, AK; Writing – review & editing: FB, GS. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Зниження ударного шуму за рахунок застосування сталей з підвищеними дисипативними властивостями при виготовленні деталей гірничого устаткування

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Мета. Дослідження впливу легуючих елементів на властивості сталей, що сприяють підвищенню дисипації звукової енергії та зниженню акустичної емісії, з метою розробки сплавів для виготовлення деталей гірничого обладнання, працюючих в ударному режимі (бурова штанга та корпус бурової коронки).

Методика. В рамках дослідження на основі стандартних сталей було розроблено шість сплавів. Виплавка дослідних зразків здійснювалася у високочастотній індукційній печі ЛПЗ-1-67 при температурі плавлення 1700°C. Усі зразки виконували у вигляді пластин розміром 50×50×5 мм. Для дослідження рівня ударного шуму застосовувалась установка “КазНТУ-2017”. Калібрування звукового сигналу здійснювалося за допомогою генератора ЗГ-10. Корекція результатів залежно від атмосферного тиску проводилася із використанням пістонфону PF-101. Температура та вологість повітря у лабораторії підтримувалися на постійному рівні. Акустичні вимірювання проводилися п’ять разів, з подальшим усередненням результатів.

Результати. Розроблені сплави №4 і №6 мають підвищені дисипативні характеристики, що дозволяє віднести їх до категорії «тихих» сталей. Це зумовлено збільшеним вмістом графіту та фериту в їх структурі, що сприяє ефективному поглинанню звукової енергії. Сплав №3 характеризується середніми дисипативними властивостями через наявність залишкового цементиту у структурі.

Наукова новизна. Встановлено, що у сплавів №3, 4 і 6 логарифмічний декремент затухання (δ) у 2 рази вище, відносне розсіювання (ψ) у 3 рази вище, а внутрішнє тертя (Q^{-1}) також у 3 рази перевищує показники стандартних марок сталей, які застосовуються в деталях гірничих машин.

Практична значимість. Розроблені сплави №3, 4 і 6 рекомендується використовувати при виготовленні деталей гірничого обладнання. Їхні підвищені дисипативні властивості забезпечують зниження рівня шуму бурової штанги та корпусу коронки на 10-12 дБА, сприяють збільшенню ресурсу роботи вузлів, а також покращенню умов праці робітників гірничодобувної галузі.

Ключові слова: *гірниче обладнання, сталь, сплав, рівень звуку, інтенсивність шуму, швидкість затухання, внутрішнє тертя*

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