The object of research is the hygienic characteristics of harmful substances that pollute the air during contact butt welding with continuous and pulsating melting. The task to be solved is the lack of such information for devising appropriate measures to protect operators of contact welding of railroad rails. A description of the methods of researching the chemical composition of welding aerosols and gases, the dispersed composition of nano-sized fractions of aerosols and assessing their impact on the body of welders is given. It was established that contact butt welding by melting P65 rails is accompanied by the release of harmful substances into the air of the working zone in the form of aerosols at the nano range level, which are characterized by high biological activity. The research results showed that during continuous melting, the intensity of welding aerosol release is lower than during pulsating melting. It is shown that the toxicity of the aerosol during contact welding belongs to the moderately dangerous class. It was established that during contact butt welding by melting, an aerosol is formed, the composition of which contains nano-sized components of manganese and iron in concentrations that exceed the calculated approximately safe levels of human exposure. In the aerosol sample, particles ranging in size from 70.8 to 1071.8 nm were detected, and the average aerodynamic diameter of the aerosol particles was 295.2 nm. The studies have shown that melting butt welding is accompanied by the formation of such toxic gases as nitrogen dioxide and carbon monoxide in concentrations that exceed the maximum permissible. The results of a comprehensive hygienic assessment of aerosols during contact butt fusion welding provided comprehensive information about the level of harmful effects of these aerosols on the body of welders

Keywords: contact welding, harmful substances, nano-sized particles, protective measures

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IDENTIFYING PATTERNS OF AEROSOLS FORMATION DURING CONTACT BUTT FUSION WELDING

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1. Introduction

All over the world, during the construction of non-contact tracks of high-speed railroad lines, high-strength rails are used. For their connection, contact butt fusion welding (CBFW) is mainly used, which has significant technical advantages compared to other welding techniques: it provides increased wear resistance and strength of welded joints [1]. However, CBFW, like most other welding techniques, has certain disadvantages associated with the presence of harmful and dangerous production factors. Among them, the most harmful for welders is the release of harmful substances into the air of the working area in the form of welding aerosol (WA). The impact of WA on the human body is unique, which is explained by its chemical and nanoscale composition, which ensures increased penetration of aerosol parts into the human body in various ways.

To protect welders, a set of well-known measures to normalize working conditions in production is used, in particular, the use of modern highly efficient ventilation systems. Thus, the existing means of local ventilation capture WA directly at the source of its formation, thus preventing its spread throughout the production premises. They remove small volumes of air using low-powered fans. However, in the case of CBFW, the intensity of WA release is almost 100 times higher than, for example, in the case of mechanized welding under a flux. At the same time, it should be taken into account that WA can be represented by solid particles smaller than 100 nm in the form of agglomerates with a volume of several to thousands of particles [2]. Therefore, there is the task of determining the quantitative and dispersed composition of WA for the development of effective filter ventilation equipment and other measures to protect welders specifically for the processes of CBFW.

Therefore, the scientific issues of protection of contact welding operators from WA have not yet been resolved. To this end, it is necessary to have data on the chemical and dispersed composition of hazardous substances, their concentration in the air of the working area, and toxicity. Therefore, the topic of creating scientific foundations for the protection of contact welding operators from WA is very relevant. In order to create proper sanitary and hygienic working conditions for the operators of CBFW during the welding of railroad rails, it is necessary to have data on the hygienic characteristics of the WA in order to devise measures to protect workers.

2. Literature review and problem statement

In modern research on contact welding, the point is usually to improve the welding technique and improve the quality of welded joints [3]. At the same time, the important issues of the harmful effect of WA, formed during welding, on the body of the operator-welder are not considered.

There are some fragmented data on welding aerosols and the diseases they cause. For example, paper [4] considers the risk factor of lung diseases from WA, which are formed during arc welding. Work [5] deals with the penetrating ability of aerosol particles of different fractions into different parts of the respiratory system and the peculiarities of their behavior in the respiratory tract. In work [6], a general classification of aerosols by size and localization in the respiratory organs and the effect of WA elements on the body was given. Questions about the dispersed composition of WA formed during contact butt fusion welding remain unsolved. And it is this issue that is the most important regarding the protection of respiratory organs of contact welding operators.

When considering the properties of aerosols, one should take into account the positions from which their hygienic evaluation is carried out [7]. For engineers of ventilation systems, the key properties of aerosol particles can be, first of all, those that determine the characteristics of their behavior in the environment. For doctors, these are the properties that characterize the effect of particles on the state of the body. The size of the particles is of decisive importance for their penetration into the respiratory organs and sedimentation in certain areas. Therefore, special attention is paid to the study of this particle parameter.

At the same time, the question arises about the mechanism of formation of WA, which actually determines their dispersed composition [8]. Thus, during contact welding of rails, the metal is first heated until a layer of molten metal is formed on the ends. In the process of convergence of the parts that are under the voltage of the source, at the moment of their contact with a relatively small pressure, electrical contacts are formed on the surface of the ends between their local areas. When a current passes through these contacts, their rapid melting and the formation of liquid metal jumpers occur. The jumpers collapse and explode and drops of molten metal are ejected from the gap in the form of sparks, which burn to form a large amount of metal vapor. After these vapors are ejected from the high-temperature zone beyond the welding zone into the low-temperature zone, they oxidize and condense into solid particles, which are the actual welding aerosol. These WA particles have very small sizes – from thousands to 10 microns [9]. That is why researchers are interested in the most important question regarding the specific size of WA particles, especially nano-sized fractions [10]. Thus, it can be seen from studies [7–10] that the issue of specific sizes of WA particles (their aerodynamic diameter and size distribution) during contact welding has not yet been determined.

A peculiarity of the toxic effect of aerosol nanoparticles formed during welding work may be that the air of the working area simultaneously contains particles of different chemical elements of different sizes [11]. WA mainly includes compounds of metals (iron, manganese, chromium, aluminum, titanium, zinc, copper, nickel, etc.), gaseous fluorine compounds, carbon oxides, nitrogen oxides, ozone, etc. [12]. The problem of determining the chemical composition of these highly dispersed particles and gases also remains unsolved, requiring the use of special procedures.

Depending on the size, aerosol particles can settle in the trachea, bronchi and bronchioles, and then be removed from these organs with the help of hairs. If the settled particles of the aerosol are soluble, then their general toxic effect on the body can be detected depending on the chemical composition of this aerosol. Particles of different sizes affect the welder's body in different ways. Particles with a diameter of less than 20 microns can remain suspended in the air, particles larger than a few micrometers settle on the walls of the body's airways and are excreted with mucus. About 30 % of particles with a size of 0.1–1 μm, as well as with a size of less than 0.1 μm (100 nm), settle in the lungs. Almost 100 % of particles with a diameter of less than 1 μm enter the body through the respiratory tract. These nanoparticles enter the circulatory system and are carried throughout the body with the blood. They can accumulate in the bone marrow, central and peripheral nervous systems, organs of the gastrointestinal tract, lungs, liver, kidneys, and lymph nodes. Nano dispersed particles of oxides of manganese, chromium, nickel, etc., can be the most toxic elements during welding work when inhaled in the form of an aerosol [13].

However, our review of literature data [5–13] shows that the issues of protection of operators of contact butt fusion welding still have a rather general nature. They do not provide complete information about the chemical and dispersed composition of such WA, which is necessary for devising appropriate means of protection for contact welding operators. Therefore, the question of researching the chemical and dispersed composition of WA, as well as determining their toxicity in order to develop appropriate protective measures, requires significant elaboration using modern procedures.

3. The aim and objectives of the study

The purpose of this study is to determine the patterns of formation of welding aerosol during contact butt fusion welding for their hygienic assessment with the aim to devise measures to protect welders. This will make it possible to develop adequate methods and means of protection for operators of contact butt fusion welding. The results of determining the emission intensity, the chemical composition of WA, and the concentration of gases can be used to calculate the required performance of local ventilation. Data on the dispersed composition of WA will be the basis for the selection of suitable filter materials for ventilation systems and means of individual respiratory protection.

To accomplish the aim, the following tasks have been set:

– to determine the intensity of formation (release), the chemical composition of WA, and the concentration of gases when using CBFW;

– to investigate the dispersed composition of WA of nano-sized fractions.

4. The study materials and methods

The object of our study is the chemical and dispersed composition of WA, formed during contact butt welding of railroad rails, as well as their toxicity based on the calculated determination of the class of these aerosols. The research was carried out by sampling WA during welding in the production premises at the Electric Welding Institute named after E. O. Paton. For this purpose, the welding of railroad rails P 65 (steel grade – K76F, cross-sectional area of the rail – 8200 mm^2) was carried out on a contact butt welding machine K 1000. Welding was carried out by continuous and pulsating melting under generally accepted modes.

The hypothesis of the research is the theoretical ideas about the process of rapid condensation of high-temperature steam of molten metal at the molecular level into solid particles of WA in the process of steam transfer to the low-temperature zone. However, these WA particles also coagulate (stick together), increasing in size, which is the reason for the formation of a nanosized aerosol.

At the same time, simplifications were adopted that the process of steam condensation into solid particles is accompanied by their simultaneous oxidation, as a result of which it is possible to assume that WA particles should consist of metal oxides. But the accepted chemical analysis procedure makes it possible to determine the content of harmful substances of WA only in the form of elements of manganese, aluminum, iron, and other substances, which is enough for a reliable interpretation of the toxicity of WA.

The study of the intensity of WA emissions was carried out by the gravimetric method by taking samples of WA during the welding process; determining the chemical composition of WA – by photocolorimetry methods. Determination of WA toxicity (limit value and WA hygienic class) – by calculation method in accordance with methodological standard ISO 15011-4:2008.

The scheme of the bench for sampling WA during contact butt welding on the K1000 installation is shown in Fig. 1.

WA samples were taken during the operation of the K1000 installation (contact butt welding, R-65 rail profile, welding time 141 s, sampling time 30 min, 15 dm^3 of air was sampled at a rate of 0.5 dm^3/min).

To study the mass concentration of suspended particles and the concentration of chemical substances, air with a volumetric flow rate of 0.5 dm^3/min was aspirated using a sampler “Typhoon R-20-2” (Ukraine) through a special absorber. The selected sample was filtered using a syringe with an attached filter holder with a membrane disk filter “Domnick Hunter” (England) with a diameter of 25 mm and a pore size of 100 nm [14].

The size of solid particles in the WA sample was determined by two methods: the Pade-Laplace method and the cumulant method (to increase the reliability of the results). The method of dynamic light scattering was applied using the Analysette 12 DynaSizer device (Fritsch, Germany) [14].

The chemical composition of air samples was determined by optical emission spectrometry with inductively coupled plasma (OEC-IZP) using the device “Optima 2100 DV” (PerkinElmer, USA) [15].

Determination of the concentration of CO and NO_2 gases in the air of the working area was carried out with the help of gas analyzers “Aquilon-1-1” and “Aquilon-1-2”, respectively.

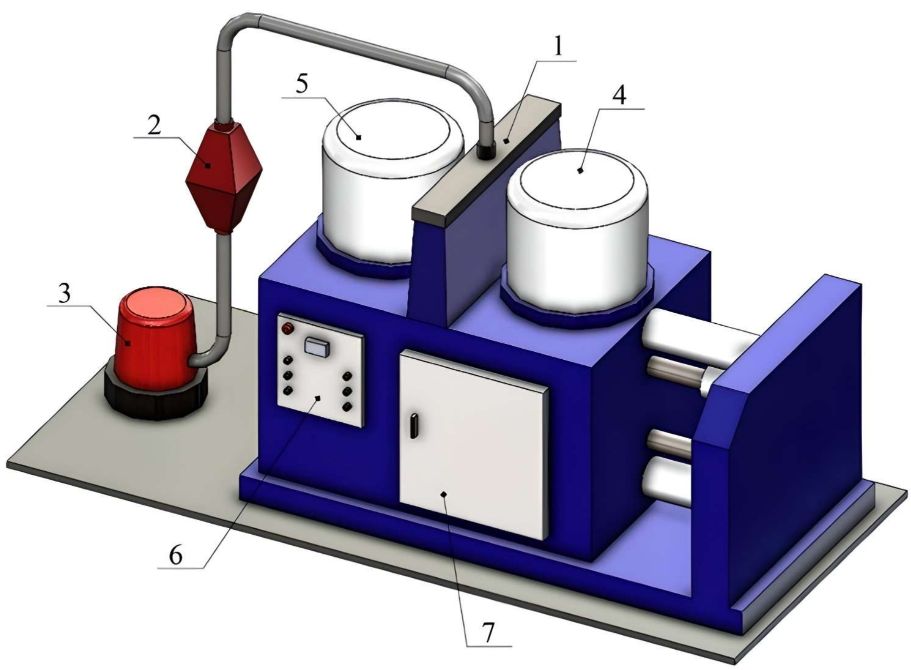

Fig. 1. Aerosol sampling scheme during contact butt welding on the K1000 installation: 1 — sampling nozzle (covering the welding zone); 2 — the chamber of the filter holder with a filter made of FPP fabric; 3 — thrust exciter; 4 — stationary column; 5 — moving column; 6 — control unit; 7 — the door that closes the electrode clamps

5. Results of research on the hygienic characteristics of welding aerosols during contact butt fusion welding

5. 1. Determination of chemical composition, intensity of welding aerosols, and gas concentration

The welding modes and the results of determining the intensity of WA release during contact butt welding with continuous and pulsating fusion of rails P 65 are given in Table 1.

Table 1

Welding mode and intensity of welding aerosol release during contact butt welding with continuous and pulsating fusion

Welding mode	f, Hz	I_w, A	U_w, V	t_w, s	V_a, g/min	V_{Mn}, g/min	V_{Al}, g/min
Continuous	50	9,464	6.8	141	2.61	0.040	0.039
Pulsating	50	24,752	6.5	101	3.54	0.054	0.053

Note: f, Hz – current frequency; I_w, A – strength of the welding current; U_w, B – welding voltage; t_w, s – welding time; V_a, g/min – the intensity of WA release per minute; V_{Mn} – intensity of manganese release; V_{Al} – intensity of aluminum release

The results of determination of the intensity of WA release, which was formed during continuous and pulsating melting of P65 rails, are given in Table 1. They indicate that the intensity of WA discharge increases with pulsating fused rails.

Analysis of the chemical composition of WA (Table 2) revealed that it contains such harmful components as manganese and aluminum in small quantities. Accordingly, the rest of the WA components belong to iron, which is the predominant amount both in the composition of the rails and in the composition of the WA. The intensity of the release of these components (Table 1) varied according to the fusion technique. For continuous contact butt fusion welding, these values were lower since in this case higher currents were used.

Table 2

The chemical composition of the welding aerosol formed during contact butt fusion welding

Substance	Mn	Al	Fe
wt%	1.53	1.15	Rest

ISO 15011-4:2008 methodical standard was used to calculate the final indicators of the hygienic assessment of CBFW. The results of the calculations, that is, the hygienic class of this welding method, are given in Table 3.

According to the WA classification in accordance with this standard, the smallest values of the intensity of their release belong to the "A" class mark, and the largest – "E". The digital class of WA can vary from 0 to 5:0 – the most harmful; 5 is the least harmful. The class number of the welding technique indicates the corresponding toxicity of WA and its approximate concentration, which must be observed. The two-digit designation of the class with a number and a letter makes it possible to obtain a general indicator of the degree of influence of WA on the welder's body.

According to our calculations (Table 3), the level of release of WA during both continuous and pulsating contact welding of P65 rails belongs to the same class – "4d". This class is characterized by fluctuations in the intensity of WA release from 15 to 25 mg/s, and the limit value of WA toxicity $LV_{WF(A)}$ is within 3.5...4.5 mg/m^3.

Table 3

Indicators of hygienic assessment of contact butt welding by continuous and pulsating fusion of P 65 rails

Welding mode	I_w, A	V_a, mg/s	$LV_{WF(A)}$, mg/m^3	Hygienic class
Continuous	9,464	14.5	3.874	4d
Pulsating	24,752	19.7	3.874	4d

An important factor affecting working conditions during welding is the presence of such gases as carbon monoxide CO and nitrogen dioxide NO_2 in the air of the working area. The concentration of these gases in the welding zone is regulated by sanitary regulations [16].

The results of studies of the concentration of CO and NO_2 at the workplace at the CBFW of rails P 65, depending on the welding mode, are given in Table 4 taking into account the measurement error.

The results of these studies showed that the concentration of carbon monoxide increases with an increase in the welding current and may exceed the maximum permissible concentration (MPC), which is 20 mg/m^3 according to the regulatory value [16]. The concentration of nitrogen dioxide does not change significantly and does not exceed the MPC (2 mg/m^3). At the same time, more carbon monoxide is released during pulsating fusion, and more nitrogen dioxide is released during continuous fusion.

Table 4

Concentration of CO and NO_2 at the workplace during butt welding under different welding modes

Welding mode Continuous	I_w, kA	Mass concentration, mg/m^3	
		CO	NO_2
Pulsating	9.464	18.8±2.0	1.3±0.5
Welding mode	24.752	20.4±2.1	1.2±0.5

5. 2. Results of research on the dispersed composition of welding aerosols of nano-sized fractions

The results of studies of the dispersed composition of WA nano-sized fractions during contact welding by continuous fusion, performed by the Padé-Laplace and cumulant methods, are shown in Fig. 2–4. The two specified methods were used to increase the reliability of research results. At the same time, the intensity of the radiated signal created by the irradiation of WA particles, the volume occupied by the particles in the sample, and the number of particles in the sample were recorded. Thus, it was established that the average aerodynamic diameter of WA particles is 295.2 nm.

The results of these studies showed that the data obtained by the cumulant method correspond to the data obtained by the Pade-Laplace method.

In particular, the average aerodynamic diameter of WA particles in the sample is 310.13 nm, while the average diameter according to the emitted signal intensity is 341.77 nm. According to the occupied volume, the average diameter of WA is 371.86 nm, and according to the number of particles in the sample, it is 236.41 nm (Fig. 5–7). However, in the sample of WA, particles with a size from 70.81 nm to 1071.8 nm were detected.

The results of determination of the average aerodynamic diameter of WA, selected during contact butt welding by pulsating fusion showed the following. According to the

Pade-Laplace method, based on the intensity of the emitted signal, the volume occupied and the number of particles in the sample, this particle diameter is 295.2 nm, as in the case of continuous fusion.

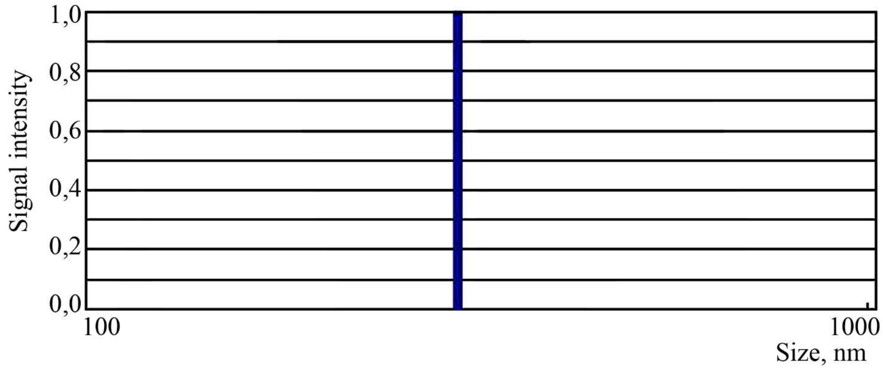

Fig. 2. The average diameter of aerosol particles according to the intensity of the signal emitted by the particles (Padé-Laplace method)

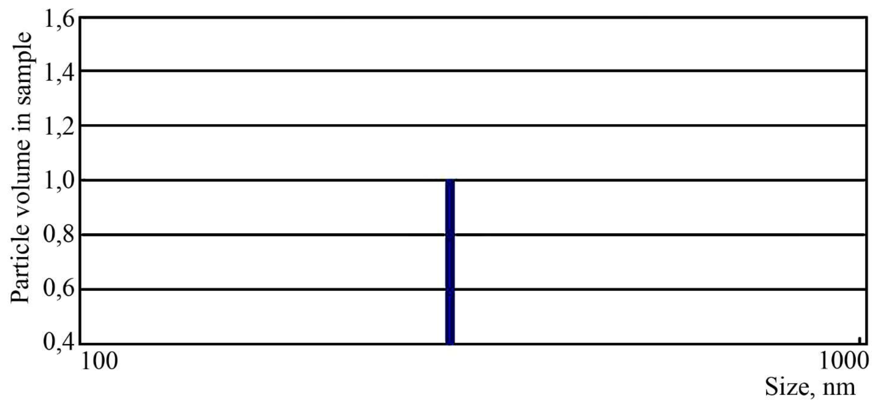

Fig. 3. Average diameter of aerosol particles by occupied volume (Padé-Laplace method)

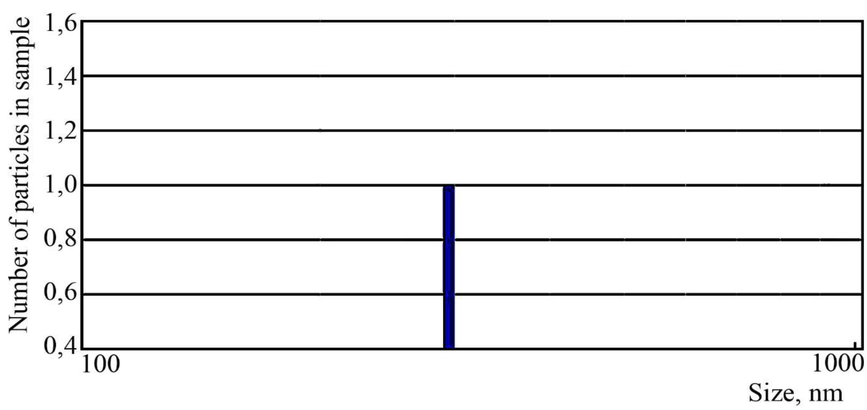

Fig. 4. The average diameter of aerosol particles by the number of particles in the sample (Padé-Laplace method)

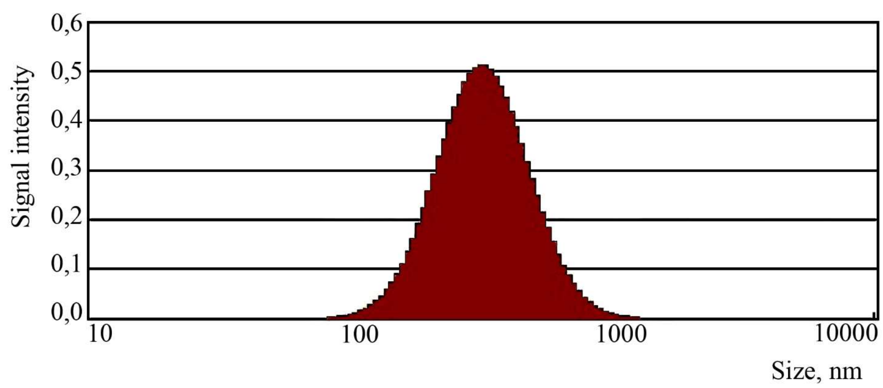

Fig. 5. Distribution of the size of aerosol particles according to the intensity of the signal emitted by the particles (cumulant method)

At the same time, as can be seen from Fig. 8, 9, the distribution of particles into fractions is observed in the sample, namely, 62 % of the volume is occupied by particles with a size of 145.54 nm. There is also a fraction with an average size of 1698.69 nm (38 % of the volume), which can be explained by the agglomeration of particles in the time interval from sampling to the moment of their investigation (24 h).

In turn, the cumulant method established that the average aerodynamic diameter of the particles in the WA sample is 292.2 nm, and the average diameter according to the intensity of the emitted signal is 311.01 nm. According to the occupied volume – 334.53 nm and according to the number of particles in the sample – 251.97 nm. In addition, particles ranging in size from 102.36 to 851.36 nm were detected in the sample.

Analyzing WA samples taken during contact butt welding by continuous fusion, it should be noted that very similar data were obtained using both applied methods (Padé-Laplace and cumulant). This testifies to the adequacy of our results regarding the size of the particles that were formed both after contact butt welding by continuous and pulsating fusion.

Further studies of the chemical composition of WA, selected at CBFW, were carried out using the OES-IZP method. This method made it possible to detect the following chemical elements in the highly dispersed/nanosized state (less than 100 nm) in the selected air samples: manganese, aluminum, iron (Table 5). Along with this, for the hygienic evaluation of these substances in the nanoscale state, the calculation of approximately safe levels of exposure (ASLE) to the human body was performed [15]. This calculated value of ASLE can be used as an additional control method for the implementation (if necessary) of management decisions to minimize the impact of harmful substances on the body of employees. The calculation of ASLE for chemicals in the nanoscale state was carried out using the coefficients recommended by the British Standards Institute ISO 15202-2:2020(en) and in accordance with methodological recommendations [15].

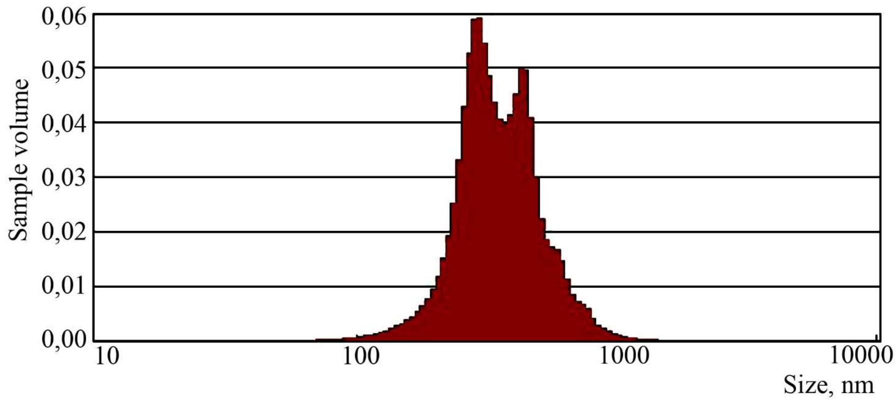

Fig. 6. Aerosol particle size distribution according to the occupied volume in the sample (cumulant method)

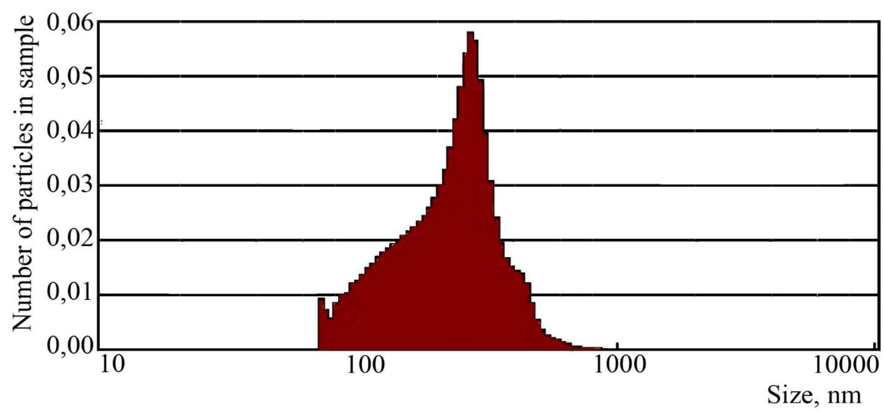

Fig. 7. Size distribution of aerosol particles by number in the sample (cumulative method)

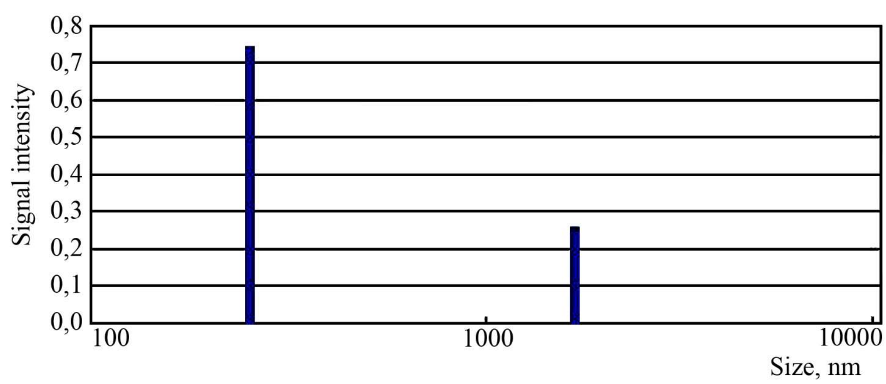

Fig. 8. Average diameter of aerosol particles according to the intensity of the emitted signal (Pade-Laplace method)

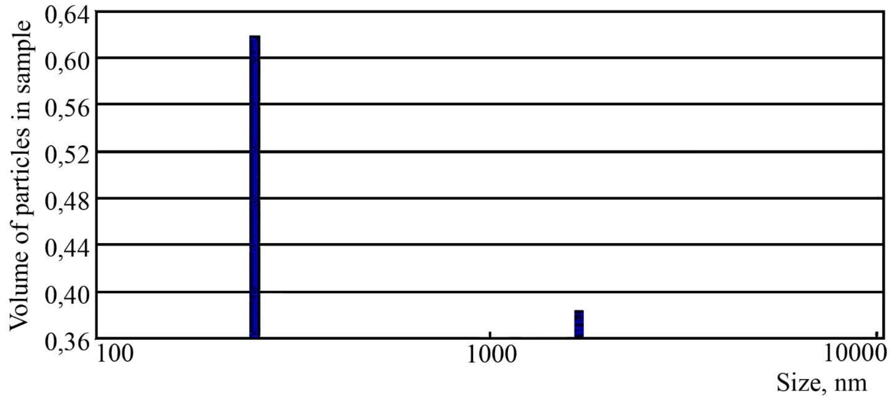

Fig. 9. Average diameter of aerosol particles by particle volume in the sample (Pade-Laplace method)

So, as can be seen from Table 5, the concentrations of nano-sized particles of manganese and iron are such that they exceed the calculated values of ASLE. To some extent, this indicates that in this case, the toxicity of WA is mainly determined by manganese and iron, which should be taken into account when developing protective measures. At the same time, the concentration of aluminum in the air of the working areas does not exceed ASLE.

Table 5

The content of chemical elements in a highly dispersed state, selected during contact butt fusion welding

Element	Content in liquid (mg/l)	Content in air (mg/m^3)	ASLE, mg/m^3
Mn	0.042±0.001	0.027±0.0006	0.01
Fe	1.130±0.1	0.74±0.06	0.6
Al	0.18±0.005	0.12±0.004	0.2

6. Discussion of results of investigating the hygienic characteristics of welding aerosols

Analysis of the chemical composition of WA (Table 2) showed that it contains such harmful components as manganese and aluminum in small quantities. Their mass fraction in the aerosol is insignificant, which is due to the low content of these components in the P 65 rails that were welded. Accordingly, the rest of the WA components belong to iron, which is the predominant amount both in the composition of the rails and in the composition of the WA.

As can be seen from Table 1, a current more than 2.5 times higher was used in contact butt welding by pulsating fusion than in contact butt welding by continuous fusion. That is why the intensity of the release of WA and its individual components increases with an increase in the welding current. However, this growth (Table 1) is explained not only by the greater current strength in this case but also by the influence of the current pulses themselves on the release of WA. At the moment of the maximum increase in the current strength of each pulse, there is a sharp emission of vapor of molten metal beyond the melting zone. This contributes to the additional emission of steam and the formation of a larger amount of aerosol [17]. Moreover, the sharp explosive emission of metal vapors beyond the contact gap leads to the non-equilibrium formation of WA, which ensures a low content of toxic volatile manganese in the composition of this aerosol (no more than 1.53 %). And during arc welding in shielding gases of low-alloyed steels at different modes, the manganese content in WA can vary from 8.5 to 17.7 % [17], which is mainly due to the equilibrium formation of an aerosol. This indicates significant sanitary and hygienic advantages of contact butt welding by fusion in comparison with arc welding.

Along with the fact that it concerns the toxicity of these WA, regardless of the intensity of release, the calculated final indicators of the hygienic assessment of CBFW in accordance with ISO 15011-4:2008 show the following. Both during continuous and pulsating welding of P 65 rails, these aerosols belong to the same class – “4d” (Table 3). This indicates their relatively equal harmful effect on the body of welders.

The results of determination of CO concentration at the workplace (Table 4) showed that only during butt welding with pulsating fusion, the concentration of monoxide exceeds the limit value [16]. In other cases, this does not happen. This should be taken into account when devising protection measures for welders.

The increased level of carbon monoxide during pulsating fusion can be explained by a higher current and, accordingly, an increased temperature in the joint gap at the molten ends of the rails. This leads to an increase in the intensity of oxidation of the metal and, in particular, of the carbon contained in the metal of the rails.

The reason for the formation of nitrogen dioxide is mainly the photochemical action of ultraviolet radiation [17] in the junction gap, which leads to an increase in the intensity of nitrogen oxidation of the air to dioxide. Therefore, during contact welding with continuous fusion, ultraviolet radiation acts on nitrogen and oxygen in the air without pauses, and therefore this oxidation does not stop compared to pulsating fusion.

The results of studies of the average aerodynamic diameter (Fig. 2–4, 8, 9) and the size distribution of nanosized aerosols (Fig. 5–7) make it possible to choose suitable filter materials for air purification systems. They showed that such data can be obtained using the Pade-Laplace and cumulant methods, which is necessary for similar studies of other welding methods.

Hygienic evaluation of the effect of the size of solid particles of WA on the human body based on the calculation of ASLE [15] showed that the concentrations of nano-sized particles of these aerosols, which are released during CBFW, exceed their limit values. These results, which show how the size of WA particles affects their harmful effect on welders, must be taken into account when designing filter materials for ventilation systems and individual respiratory protection.

Thus, our results of this comprehensive assessment of the hygienic characteristics of WA that pollute the air of the working area at CBFW provided comprehensive information about the level of harmful effects of these WA on the body of welders. These data should be used to devise adequate measures and means of protection for welding operators and others working in production facilities where CBFW is used. At the same time, for the final hygienic evaluation of CBFW, taking into account other harmful and dangerous factors, one should also use the previously found results on the electromagnetic safety of welders at CBFW [18]. We believe that similar studies should be conducted for the hygienic evaluation of other welding techniques.

The limitation of this study is that the use of a membrane disk filter "Domnick Hunter" makes it possible to select nanoparticles of manganese, aluminum, and iron with a size of no more than 100 nm. This somewhat complicates a more in-depth further analysis of the selected samples regarding the potential impact on workers and the environment.

A methodological shortcoming of the study is the use of glucose-citrate buffer as a stabilizer of the selected air samples, which is expedient from the point of view of further biomedical studies of nano-sized fractions of WA. However, this does not exclude agglomeration processes, in particular, temporary agglomeration of nanoparticles in the selected samples, the consequence of which is fixation in the process of analysis by the method of dynamic light scattering of particles with a diameter greater than 100 nm.

In turn, a promising area of research is the further study of the emission of nanosized chemical elements into the air of the working area with the aim of improving welding materials and technologies, as well as the development of effective preventive protection measures.

Further advancement of our studies may face a methodological problem regarding the sampling of WA to determine the real sizes of aerosol particles of nano-sized fractions.

7. Conclusions

1. A study of the emission intensity, the chemical composition of the welding aerosol, and the concentration of gases during the application of contact butt welding by fusion of P65 railroad rails was carried out:

– it was established that fusion butt welding is accompanied by the formation of welding aerosol, nitrogen dioxide, and carbon monoxide in concentrations that exceed the maximum permissible;

– with continuous fusion, the intensity of welding aerosol release is lower than with pulsating fusion; the toxicity of the welding aerosol, both during continuous and pulsating application, belongs to the moderately dangerous class 4d; the main elements that determine the toxicity of the aerosol are manganese and iron.

2. It has been established that nanosized particles of manganese and iron are present in the composition of the aerosol during contact butt fusion welding in concentrations that exceed the calculated approximately safe levels of exposure to humans. In samples of welding aerosol, particles with a size from 70.8 nm to 1071.8 nm, which are characterized by high biological activity, were found. The average aerodynamic diameter of aerosol particles is 295.2 nm.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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