

The object of this study is the quantitative characteristics of magnetic fields induced during electric contact welding in various ways: contact point, arc-butt, capacitor point, contact-butt continuous, and pulsating fusion. The problem to be solved is the lack of necessary information regarding the electromagnetic safety of these welding techniques. A description of the proposed methodological approaches to determining the levels of magnetic fields, their measurement tools, and methods for assessing their impact on the welder's body is given. Based on the analysis and processing of the acquired oscillograms and spectrograms of magnetic fields, their quantitative characteristics were measured. To determine the general level of the polyfrequency magnetic field arising at contact welding, the proposed generalized indicator of the level of the magnetic field was used. It was established that during contact point welding by a stationary machine, the level of the magnetic field exceeds the maximum permissible value at the workplace in the range of 50–1000 Hz at a distance of 0.3 m from the welding electrodes. When manually welding in this way, the magnetic field level exceeds the permissible level in the frequency bands of 5–50, 50–1000 Hz directly near the electrical cable. Capacitor spot welding with direct current is characterized by exceeding the maximum permissible MP at the workplace in the high-frequency range of 1000–10000 Hz. During arc-butt welding, no excess of the maximum permissible levels of the magnetic field was detected at the workplace. It is shown that the spectral composition and magnitude of the magnetic field signal is determined by the welding technique and the initial parameters of power supplies. Orimani results can be used in the field of welding production and labor protection

Keywords: contact welding, magnetic field, field intensity, oscillograms, spectrograms, welder protection

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DETERMINING PATTERNS IN THE GENERATION OF MAGNETIC FIELDS WHEN USING DIFFERENT CONTACT WELDING TECHNIQUES

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1. Introduction

Among the known techniques of fusion welding, electric contact welding occupies a prominent place. The use of this technique for joining metals, its relative simplicity, the absence of any requirements for the initial state of welding surfaces makes it possible to solve many complex technical problems in various industries and construction. This technological process can be used for welding all metals and alloys that are used in industry. However, as practice has shown, the operation of electric welding is accompanied by the generation of increased levels of electromagnetic radiation, harmful, and, in certain cases, dangerous to the human body [1]. Therefore, the issues of electromagnetic safety of production equipment, the effect of electromagnetic fields on the human body, as well as the creation of appropriate measures and means of protection against them, are relevant [2]. Depending on the welding

technique, the type of equipment, and the distance to it of the welder, the levels of the magnetic component of the electromagnetic field, that is, the intensity of magnetic fields (MF) may exceed the maximum permissible levels [3]. Such MF can be dangerous to the human body: they can cause diseases of the central nervous and cardiovascular systems, destroy human tissue cells, have a carcinogenic effect, etc.

Therefore, there was an urgent need to conduct research on the levels of MF when using welding equipment of various types in order to hygienically assess them and devise methods and means of protecting welders.

2. Literature review and problem statement

In works related to contact welding, the authors typically argue about improving welding technology, in particular

in [4] – about equipping welding equipment with additional devices to obtain in-depth knowledge of the quality of the welded joint. A characteristic feature of such studies is the use of magnetic support for contact welding [5], that is, the action of a magnetic field on the welded joint being created in order to improve its quality [6]. At the same time, the issues of determining the harmful effect of the magnetic field induced during contact welding on the body of the welder operator remain unresolved.

An analysis of the latest literature on MF in the workplaces of welders shows that they have not been studied enough. Thus, in [7], some results of measurements of MF levels at the workplace of electric arc welding with a metal electrode in active gas in accordance with the current European Directive 2013/35/EC are reported. The obtained results of MF levels in the frequency band from 5 to 400 kHz showed that they significantly exceed the levels of MF created by other types of electrical equipment. This is explained by the fact that in arc welding, relatively high electric currents (up to several hundred amperes) are used.

In [8], it was confirmed that semi-automatic welding with a metal electrode in carbon dioxide is characterized by an increased level of magnetic field in the frequency range of 50–1000 Hz. During arc welding under flux, exceeding the maximum permissible levels of individual harmonics of the magnetic field was not detected but there is an excess of the total value of all harmonic components of the MF. During manual arc welding with coated electrodes, the exceeded level of the magnetic field is registered only on the electrode cable. It was shown that the spectral composition of the magnetic field signal is determined mainly by the welding technique, the features of arc combustion, and the nature of the transfer of the electrode metal in the arc gap, as well as the initial parameters of the power sources of the welding arc.

In [9], which tackles contact spot welding, it was shown that during the operation of equipment for this type of welding, MF levels are much higher than in arc welding. The authors found a significant excess of the MF level in a wide frequency range and showed how its level decreases with increasing distance from the welding electrodes. The results of work [10] confirmed this pattern and showed that the MF, which are created by the contact welding equipment, have a wide frequency composition and require the improvement of the method of their evaluation. For this, it is necessary to have a generalizing indicator of the MF level, which must take into account all its harmonic components.

Thus, the review of literary data shows that the issues of electromagnetic safety of contact welding processes remain unresolved. Therefore, the issues of modernization of welding equipment, the creation of methods for protecting welders, as well as methodological approaches to assessing the hygienic characteristics of polyfrequency MF, require significant refinement.

3. The aim and objectives of the study

The aim of our study is to determine the patterns of creation of magnetic fields in various techniques of contact welding to devise recommendations for the modernization of welding equipment and improving the methods of protection of welders.

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

- to determine the indicators of magnetic field levels (intensity in the established frequency ranges, the total level of

MF, and the permissible operating time of the welder when using various techniques of contact welding);

- to give a hygienic assessment of MF in accordance with sanitary standards for the further development of recommendations for the protection of welders from MF.

4. The study materials and methods

The object of research is the quantitative characteristics of magnetic fields created by the equipment of electric contact welding of various types. For this purpose, a hygienic assessment of the level of MF is performed, which implies measuring its intensity and comparing with the current sanitary standards [11].

The experiments were carried out in the welding laboratories at the Institute of Electric Welding named after E. O. Paton (Ukraine) at typical workplaces and workplaces of the private joint-stock company “Boryspil Automobile Plant” (PJSC “BAZ”, Ukraine). MF intensity measurements were performed when using the following contact welding techniques: contact point, arc-butt, point capacitor, contact-butt continuous, and pulsating fusion.

Evaluation of the parameters of MF at the workplace of welders was carried out in the following sequence:

- determining the zone of possible location of the worker near the electrical equipment during the passage of welding current;
- selection in this zone of points as close as possible to the source of the magnetic field;
- determination of frequency ranges of radiation and measurement of magnetic field strength at these points and ranges;
- determination of the permissible operating time of the welder.

To measure the strength of MF, a remote sensor (magnetic field converter), an integrating RC circuit, and a recording device were used, which included a digital storage oscilloscope with the Fourier transform rapid function with an expansion unit. The following devices were used:

- magnetic field sensor DMF-1 (Ukraine);
- magnetic field induction meter GFI-1 (Ukraine);
- magnetic field induction meter TP2-2U-01 (Ukraine);
- PCS-500 oscilloscope with PC (Velleman, Belgium);
- oscilloscope with digital storage TDS 1002 (Tektronix, USA).

According to the generally accepted methodology [11], the measurement of MF levels was performed at all sensitive points of the human body, which may be exposed to the dangerous and harmful effects of MF. These mainly include the following points: brain, heart and lungs (chest), urogenital organs (abdomen), hands. Since the electrical cable can touch the body of the welder, it is also necessary to determine the strength of MF.

In the process of measuring the strength of MF, the sensor was introduced into the field under study and oriented in space according to the maximum readings of the recording device. Three measurements were performed in the form of short pulses with a long duration period. In this case, the sensor was placed sequentially in three mutually perpendicular planes and we recorded its readings in each plane. The amplitude value of the intensity vector of MF was determined by formula [11]:

$$H_m = \sqrt{H_x^2 + H_y^2 + H_z^2}, \quad (1)$$

where H_x, H_y, H_z – the value of MF intensity in each plane.

The total value of the magnetic field strength H was determined by expression [11]:

$$H = \sqrt{H_1^2 + H_2^2 + \dots + H_n^2}, \tag{2}$$

where H_n is the magnetic field strength of the individual harmonic.

For an objective assessment of the total energy load of MF on the human body, it is necessary to take into account all the harmonic components of MF. Therefore, for the frequency range ≤ 300 MHz, in which the sources of MF operate and for which different GDRs are set, the following requirements must be observed [11]:

$$\frac{H_1^2}{H_{MP1}^2} + \frac{H_2^2}{H_{MP2}^2} + \dots + \frac{H_n^2}{H_{MPn}^2} \leq 1, \tag{3}$$

where H_1, H_2, H_n – actual intensity of MF in different frequency ranges, A/m; $H_{MP1}, H_{MP2}, H_{MPn}$ – the maximum permissible level in the corresponding frequency bands, A/m.

The same applies to the harmonic components of MF of one radiation source. Therefore, denoting the sum of the ratios of expression (3) as MFI (magnetic field indicator), it can be represented as follows:

$$MFI = \sum \frac{H_n^2}{H_{MPn}^2} \leq 1. \tag{4}$$

If this ratio exceeds unity, then it shows how many times MF level exceeds the standard value of the energy load of MF on the welder’s body. So, this ratio is nothing more than a generalized indicator of the level of the magnetic field MFI [10].

Therefore, if $MFI > 1$, then appropriate protection measures for contact welding operators should be applied at workplaces, which would ensure safe working conditions during the eight-hour work shift. Also, according to the established standard [11], time protection can be applied, that is, the allowable operating time of the welder ($T_{Al.op.t.}$) can be reduced in accordance with the value of MFI

$$T_{Al.op.t.} = \frac{8}{MFI}. \tag{5}$$

Thus, the calculation of MFI indicator by ratio (4) makes it possible to perform an objective hygienic assessment of the

overall effect of MF on the welder’s body. In this case, $T_{Al.op.t.}$, determined from formula (5), regulates the allowable time of the welder’s work during an eight-hour work shift.

5. The results of studies of levels of magnetic fields

5.1. Determination of indicators of magnetic levels

Tables 1–4 give the results of measurements and calculation of the indicator of MF–MFI level for each technique, welding mode, and frequency range in accordance with the requirements of sanitary standards [11]. At the same time, the use of such an indicator as the permissible time of MF influence on the welder ($T_{Al.op.t.}$) makes it possible to assess the level of MF and its effect on the human body most conveniently for mental perception.

Below are the results of research for each technique of contact welding.

The results of studies of indicators of the level of MF obtained by contact point welding (Table 1), their oscillograms (Fig. 1), and spectrograms (Fig. 2) showed that for this welding technique on alternating current (50 Hz), the following characteristic patterns were revealed:

- the shape of the welding current in the form of a short pack (packs) of sinusoidal pulses (that is, segments of a sine wave) determines the spectrum of MF, which has a transient character (intermediate between discrete and solid). The components of the spectrum in the frequency range of 50–1000 Hz mainly determine the sanitary problems of this technique;
- the modes used for spot welding can be considered quite monotonous relative to the resulting spectra. They do not have a significant impact on the composition of MF, the number of pulses in the pack or the number of packs (up to 3: heating, welding, releasing);
- phase regulation of welding current can have a significant impact on the magnetic situation in the working area, which leads to its sharp deterioration. In this case, MF spectrum is shifted to the right with the main harmonic of 100 Hz (Table 1, oscillogram and spectrogram of contact spot welding on a stationary machine MT-2202 with phase regulation). Permissible operating time of the welder $T_{Al.op.t.} \approx 0.34$ hours (20 minutes);
- modulation of the anterior and posterior fronts of pulses does not have a significant effect on the spectra (even, one might say, has a positive effect).

Table 1

Results of determining the magnetic field strength during contact point welding

Brand of equipment, welding method, type of current	Welding mode		Frequency range, Hz	MF intensity, A/m	MF level indicator MFI	Allowable welder’s operating time, hours (minutes)	Measurement zone	Notes
	Cycle time, s	Transformer power degree						
MT-2202, stationary machine, spot welding, alternating current	0.416	IV	50–1,000	18–265	23.7	0.34 (20)	Belly	Measurements were performed at a distance of 0.3 m from the point of contact of the electrodes
			50–1,000	10–282	24.3	0.34 (20)	Feet	
MTP-1110, manual contact spot welding, AC	0.650	I	5–50	16–195	0.03	>8	Electrical cable	Measurements were made near the cable
			50–1,000	7–146	4.2	1.94		
		IV	5–50	63–9634	52	0.16		
			50–1,000	16–2834	1720	0.005		

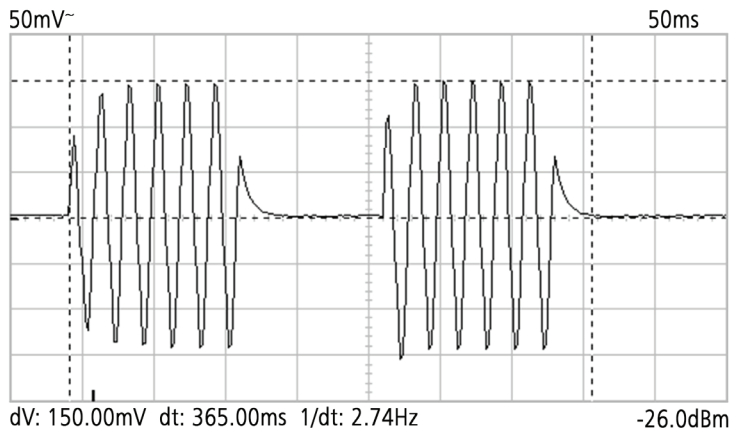


Fig. 1. Oscillogram of the magnetic field of contact spot welding on a stationary machine MT-2202

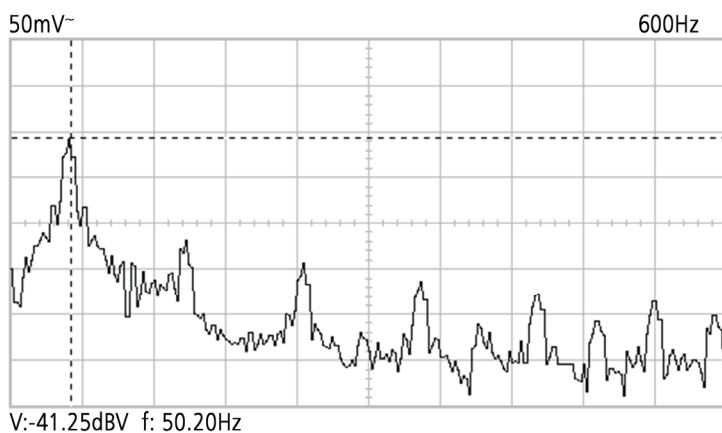


Fig. 2. Spectrogram of the magnetic field of contact spot welding on a stationary machine MT-2202

When welding sheet metal on the stationary machine MT-2202 at a maximum current (IV degree), the indicator of the maximum level of MF MFI in the range of often 50–1000 Hz in the abdomen and legs area was 24.3, which is significantly higher than unity. Accordingly, the allowable operating time of the welder is only 0.34 hours (that is, 20 minutes) for an eight-hour work shift.

Even worse hygienic results (Table 1) were obtained by manual contact welding with a gun. In the photographs (Fig. 3), taken in the production conditions of PJSC “BAZ” in the manufacture of the body of the minibus “Etalon”, one can observe the spatial placement of the working tool (gun) relative to the body of the welder during welding.

Analysis of the obtained data shows (Table 1) that the permissible operating time of the welder $T_{Al.op.t.}$ in this technological operation must be no more than 0.005 hours (18 seconds).

As can be seen from the photographs (Fig. 3), the welder periodically holds the welding tool in the head area and at the level of the belt. This is what can negatively affect such sensitive (relatively harmful effects of MF) organs of the human body as the brain, heart, and genitourinary organs. This indicates that this welding technique cannot be performed manually at all.

Spot welding can only be performed in a stationary way on special welding machines, provided that the welder's workplace is at a certain safe distance from the welding electrodes.

The study of MF arising from manual arc-butt welding was carried out with an ELOTOP gun from KOSTER (Germany).

Studs with a diameter of 3–6 mm were welded to metal sheets with pulsed direct current. An electric current rectifier without phase control of thyristors was used as a current source.

In this case, the characteristic of MF will be completely different (Table 2) compared to the previous technique of manual contact welding (Table 1). The spectrum of MF signal is continuous and is shifted mainly to the frequency range of 0–5 and 5–50 Hz with less rigid GDR. In the area of the welder's legs and arms, in this frequency range, MFI has too low values, respectively, 0.004 and 0.32, which is significantly less than unity. And in the range of 50–1000 Hz – almost equal to unity (1.01). Therefore, $T_{Al.op.t.}$ is approximately 8 hours. Moreover, the instruction manual for this equipment provides recommendations for protecting the health of the welder who works directly with this equipment.

For capacitor spot welding at direct current, it is characteristic that the shape of the welding current in the form of a short-term exponential video pulse [12] determines the continuous spectrum of MF. The components of the spectrum in the frequency range of 5–1000 Hz mainly determine the sanitary problems of this technique (Table 3). Thus, in the chest area of the welder in the frequency range of 50–1000 and 1000–10000 MFI have fairly low values – 0.002 and 0.54, respectively, which is much less than unity. And in the area of the legs and arms of the welder only in the range of 1000–10000 Hz, this figure is 14.1, which determines the permissible working time of the welder – only 0.6 hours (36 minutes) during an eight-hour work shift.



Fig. 3. Manual contact spot welding of the bus body

Contact-butt electric welding with continuous melting was performed at the Institute of Electric Welding in the operator's working area (although in industry the operator, as a rule, must be at a distance of 5 m from the welded joint). We performed welding of railway rails P 65 on alternating current with a frequency of 50 Hz. Measurements of MF levels were carried out at different distances from the machine (Table 4).

This welding technique is characterized by the fact that at the optimal rate of metal melting in each half-period of alternating current, a greater number of liquid jumpers of molten metal between the ends of the welded parts necessary for the formation of a welded joint should be possible. The destruction of these jumpers is characterized by corresponding current and voltage throws. Usually, during a stable melting process, four

to seven such throws occur (that is, with main harmonics of 400–800 Hz), which significantly exceed the idle voltage of the welding transformer. This leads to an increased level of MF.

Under the conditions of the experiment specified in Table 4, the following results of measurements of MF levels at different points of the welder’s working area in different frequency ranges were obtained. In the abdomen of the welder at a distance of 0.25 and 0.5 meters, *MFI*, respectively, is 1.2 and 0.08, and $T_{Al.op.t.}$ increases from 6.6 to 8 hours. That is, at this distance, it becomes possible to apply the duration of welder operation for 8 hours.

The process of contact-butt welding by pulsating melting of rails P 65 (Table 4) consisted of two stages:

- heating the ends of the rails by continuous melting for 30 s;
- welding with pulsating melting for 60 s.

Hygienic indicators of the whole process were determined precisely by the second stage of welding (60 s) – pulsating fusion.

Under the conditions of the experiments given in Table 4, the following results of measuring MF levels were obtained. In the abdomen at a distance from the machine:

- 1) at a distance of 0.5 m from the machine (working area):

- $MFI \ll 1$ – frequency range 5–50 Hz;
- $MFI=9.23$ – frequency range 50–1,000 Hz, $T_{Al.op.t.} \approx 0.85$ hour (50 min);
- 2) at a distance of 1.0 m from the machine (working area):
- $MFI \ll 1$ – frequency range 5–50 Hz;
- $MFI=1.4$ – frequency range 50–1,000 Hz, $T_{Al.op.t.} \approx 5.7$ hours;
- 3) at a distance of 1.5 m from the machine (working area):
- $MFI \ll 1$ – frequency range 5–50 Hz;
- $MFI < 1$ – frequency range 50–1,000 Hz, $T_{Al.op.t.} = 8$ hours.

Thus, the minimum allowable time that determines the duration of the welder’s work refers to the frequency range of 50–1,000 Hz and is 0.85 hours (50 minutes).

Given that the hygienic requirements for the level of MF intensity in this case are determined only by the second stage of the process (pulsating fusion), the total allowable welding time (taking into account the safe first stage)

was $T_{Al.op.t.} = \frac{90}{60} \cdot T_{Al.op.t.2} = 1,275$ hours. If the working area is considered, for example, the distance from the machine of 0.25 m (Table 4), $T_{Al.op.t.} = \frac{90}{60} \cdot T_{Al.op.t.(0.25)} = 1,154$ h. This makes

it possible to weld only 6 joints for the work shift.

Table 2

Results of determining the magnetic field strength during contact arc-butt welding

Brand of equipment, welding method, type of current	Welding mode (cycle time, s)	Frequency range, Hz	MF intensity, A/m	Indicator of the level of MF <i>MFI</i>	Allowable welder’s operating time, hours (minutes)	Measurement zone
Pistol for welding studs «ELOTOP-502» company «Koster», arc-butt, direct pulse current	0.28 (DC pulse), current source – three-phase transformer with thyristor rectifier and electronic control unit	0–5	90–192	0.004	≈8	Legs, hands
		5–50	18–129	0.032		
		50–1,000	8–81	1.01		

Table 3

Results of determining the magnetic field strength during contact capacitor welding

Brand of equipment, welding method, type of current	Welding mode (cycle time, s)	Frequency range, Hz	MF intensity, A/m	Indicator of the level of MF <i>MFI</i>	Allowable welder’s operating time, hours (minutes)	Measurement zone
MTK-2201, stationary machine for spot capacitor welding, direct current	Voltage – 700 V, welding cycle time – 10 ms	50–1,000	6–50	0.002	0.6 (36)	Breast
		1,000–10,000	8–34	0.54		
		50–1,000	30–201	0.005		Legs, hands
		1,000–10,000	8–112	14.1		

Table 4

Results of determining the levels of MF during contact butt welding by continuous and pulsating fusion

Welding equipment, welding methods, product	Characteristics of the welding process		Measurement area	Frequency range, Hz	<i>MFI</i>	$T_{Al.op.t.}$ hours
	Process duration, s	Type of welding current				
Stationary machine for rail welding K-1000, continuous melting welding	180.0	Alternating, 50 Hz, with amplitude modulation	The welding transformer is located in the machine at the level of the abdomen. Distance from the machine body: 0.25 m	5–50	$\ll 1$	6.6
				50–100	1.2	
			0.5 m (work area)	5–50	$\ll 1$	8.0
50–100	0.08					
Stationary machine for welding rails K-1000, welding with pulsating fusion	Duration of the entire cycle 90: 30 – continuous melting (heating)	Alternating, 50 Hz	The welding transformer and machine control panel are located at the level of the abdomen. Distance from the car: 0.25 m	5–50	< 1	0.1
				50–100	85.0	
	60 – pulsating melting (welding)	Alternating, 50 Hz, with amplitude modulation	0.5 m (work area)	5–50	< 1	0.85
				50–100	9.23	
			1.0 m (work area)	5–50	$\ll 1$	6.0
				50–100	1.33	
1.5 m (work area)	5–50	$\ll 1$	> 8.0			
	50–100	< 1				

5. 2. Results of hygienic assessment of magnetic fields with different techniques of contact welding

The results of determining the indicators of MF levels (Tables 1–4) indicate that all the investigated techniques of contact welding, except for arc-butt, are characterized by an increased level of MF. They differ significantly among themselves depending on the type of power supply with electric current, power, and type of welding current.

The histogram (Fig. 4) shows the results of a comparative hygienic assessment of the investigated welding techniques according to the indicator of the maximum level of MF in the determining frequency range, which characterizes its overall effect on the welder's body.

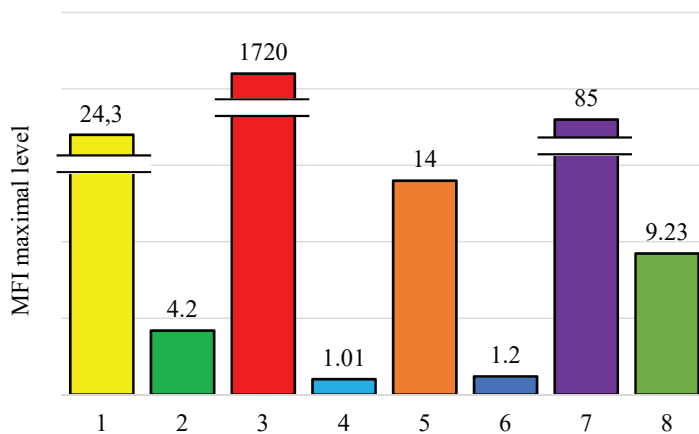


Fig. 4. Comparative hygienic characteristics of contact welding techniques: 1 – stationary spot welding by machine MT-2202 at maximum power (IV degree) with alternating current; 2 – manual spot welding by machine MTP-1110 AC at minimum power (I degree); 3 – manual spot welding by machine MTP-1110 at alternating current at maximum power (IV degree); 4 – manual arc-butt spot welding with “ELOTOP-502” gun at direct pulse current; 5 – stationary spot capacitor welding by MTK-2201 DC machine; 6 – continuous welding by machine K-1000 at alternating current with amplitude modulation; 7 – stationary welding with pulsating melting machine K-1000 at alternating current; 8 – stationary welding with a pulsating machine K-1000 at alternating current with amplitude modulation

The results of our hygienic assessment of magnetic fields in accordance with current standards [11] have made it possible to establish the following patterns:

- contact spot welding by a stationary machine is characterized by exceeding the maximum permissible level of the magnetic field at the workplace in the high-frequency range of 50–1,000 Hz at a distance of 0.3 m from the point of contact of the electrodes;

- for contact spot welding by hand, exceeding the maximum permissible level of the magnetic field takes place in the frequency ranges of 5–50, 50–1,000 Hz directly near the electrical cable;

- during arc-butt welding at the welder's workplace, no excess of the maximum permissible levels of the magnetic field was detected;

- capacitor spot welding with direct current is characterized by exceeding the maximum permissible MF at the workplace in the high-frequency range of 1,000–10,000 Hz;

- contact-butt welding is characterized by exceeding the maximum permissible level of MF in the high-frequency range of 5–50 and 50–100 Hz at a distance of up to 0.5 m from the welding machine with continuous melting and 1.5 m during pulsating melting.

The results of our studies make it possible to offer practical recommendations for minimizing the harmful effects of magnetic fields on the body of contact welding operators.

Contact spot welding is possible only if it is performed in a stationary way at minimum power with the placement of the workplace (control panel) at a certain distance from the welding electrodes.

Arc-butt welding, unlike contact spot welding, does not pose a danger to welders. Nevertheless, during manual welding, the electrode cable must be wrapped around the body of the welder.

Capacitor spot welding has a limited operating time and requires the location of the workplace at a safe distance from the welding electrodes.

When applying contact-butt welding, the operator's workplace should be located at a distance of no closer than 0.5 m from the welding machine with continuous melting and 1.5 m during pulsating melting.

6. Discussion of results of studies of magnetic field levels created by contact welding equipment in various ways

The increased levels of MF during contact spot welding by a typical MT-2202 machine are mainly due to the presence in the composition of the induced MF sufficiently intense high-frequency harmonic signals in the range of 50–1,000 Hz (Table 1). The standard values [11] in this frequency range are about 15 times lower than in the 5–50 Hz band. This is the main reason for a significant reduction in the permissible operating time of the welder operator. And with manual contact welding with a gun using the equipment MTP-1110 at maximum power (IV degree), these high-frequency harmonic signals generally create impossible working conditions for welders. In this case, the maximum level of MF is observed directly on the cable (Table 1), which supplies electric current to the welding gun. During welding, this cable is at a minimum distance from the welder's body and even in contact with him, which creates an increased danger.

Arc-butt contact spot welding with the gun “ELOTOP-502” has incomparable hygienic advantages (Table 2). This is explained by the fact that this equipment partially combines the advantages of arc welding [8] and the disadvantages of contact [9]. It operates on a constant pulse current, which is created by a three-phase transformer with a thyristor rectifier and an electronic unit for controlling an electrical signal, which reduces the possibility of generating MF due to the absence of self-induction currents. In addition, this equipment does not use a phase control device for welding current, which may also be the reason for the creation of additional MF signals. All of the above allows the welder to work a full eight-hour work shift in normal minds.

Capacitor spot welding by stationary machine MTK-2201 has significant drawbacks with respect to the level of MF (Table 3) created by direct current, which usually has hygienic advantages over alternating current. The high level of MF in this case is explained by the characteristic shape of welding current signals in the form of a short-term exponential video pulse [12], which determines the spectrum of MF. Such signals generate periodic pulsed MF of increased amplitude due to the energy that periodically arises during the charging and discharging of the capacitor of the power supply with electric current. The presence of such MFs, especially in the high frequency range of 1,000–10,000 Hz, the standard values of which are even lower than in the range of 50–1,000 Hz, significantly reduces the permissible operating time of the welder.

The results of determining the levels of MF during contact-butt welding by machine K-1000 at continuous and pulsating melting of railway rails (Table 4) show that the working conditions of the welding operator depend on the distance to the machine body. In general, when welding with continuous melting, the permissible operating time of the welder is longer than with pulsating melting. This is explained by the fact that the pulsating melting, respectively, is carried out by a pulsed alternating current with amplitude modulation, which leads to the generation of higher levels of MF due to its self-induction from these pulses. Therefore, the permissible working area of the welder with continuous melting begins at a distance of 0.5 m, and with pulsating melting – 1.5 m. This determines the place of safe location of the workplace of the operator-welder.

Thus, our results of studies of indicators of MF levels make it possible to develop recommendations for minimizing the dangerous effect of MF on the body of welders with further modernization of this contact welding equipment. At the same time, it is important to choose the right distance to the safe working area of the welding operator and the place where the welding process control panel is installed.

The results of our studies can be used in the further development of protection measures for welders working on similar contact welding equipment. Due attention should be paid to the modernization of power supplies by electric current (type of current, welding modes, welding power), the choice of a safe location of the welder for each welding technique, mechanization and robotization of welding equipment.

7. Conclusions

1. The results of determining the strength of magnetic fields in the established frequency ranges and the generalized indicator of the magnetic field level showed that by reducing its level, all the studied welding techniques can be arranged in the following order:

- manual spot welding by machine MTP-1110 at alternating current at maximum power (*MFI* magnetic field level is 1,720);
- stationary welding by pulsating melting machine K-1000 at alternating current (*MFI* – 85);
- stationary spot welding by machine MT-2202 AC (*MFI* – 24.3);

- stationary welding with a pulsating machine K-1000 at alternating current with amplitude modulation (*MFI* – 14.1);
- stationary point capacitor welding with machine MTK-2201 at direct current (*MFI* – 9.23);
- manual spot welding by machine MTP-1110 AC at minimum power (*MFI* – 4.2);
- continuous welding by machine K-1000 at alternating current with amplitude modulation (*MFI* – 1,2);
- manual arc-butt spot welding with gun “ELOTOP-502” at direct pulse current (*MFI* – 1.01).

So, the spectral composition and magnetic field strength is determined by the welding technique and the initial parameters of power supplies – by the type of current (direct, alternating, with amplitude modulation, without modulation, continuous, pulsed).

2. Based on the results of hygienic assessment of magnetic fields, practical recommendations are proposed to minimize the harmful effects of magnetic fields on the body of contact welding operators, which are as follows:

- contact spot welding is possible only if it is performed in a stationary way at minimum power with the placement of the workplace (control panel) at a certain distance from the welding electrodes;
- arc-butt welding, unlike contact spot welding, does not pose a danger to welders, however, during manual welding, the electrode cable should not wrap around the body of the welder;
- capacitor spot welding has a limited operating time and requires the location of the workplace at a safe distance from the welding electrodes;
- when using contact-butt welding, the operator’s workplace should be located at a distance of no closer than 0.5 m from the welding machine with continuous melting and –1.5 m during pulsating melting.

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Conflicts of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

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

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