

Original Article

Determination of emission of iron oxides from the welding process on the basis of mathematical models

Karolina Weronika Pikulik ¹ , Jarosław Robert Mikołajczyk ^{2*} 

¹ Laboratorium "BIOCHEMIK" Sp. z o.o., Śmiłowo, Poland; karolina.pila1@wp.pl (K.P.)

² Stanisław Staszic University of Applied Sciences in Piła, Poland

* Correspondence: jmikołajczyk@puss.pila.pl (J.M.)

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Abstract: Oxygen in metals is most often present in the form of oxides, including: FeO, Fe₂O₃, Fe₃O₄. The complexity of the welding process means that oxygen compounds can enter both the liquid metal and the atmosphere, causing negative effects. A welder is exposed to harmful emission of oxides entering the human body through the respiratory system or pores in the skin. The essence of the problem is so serious that standards for air purity and determination of amount of oxides at workplaces have been introduced. The article presents the results of research on the influence of the welding current intensity on the emission of air pollutants (in particular the emission of iron oxides) of the inhalable and respirable fractions. The bench tests were carried out on the basis of the applicable standards for air quality at welding stations. Based on the test results, on the basis of the R program, mathematical models of the emission of iron oxides generated during the welding process were developed. It was observed that with the increase of the welding current, the average value of the emission of iron oxides – both the inhalable and respirable fractions – increases. For both fractions, it was also noted that the model values are closer to the values measured in the model No. 1.

Keywords: welding smoke; respirable fraction; inhalable fraction; iron oxide

Introduction

The subject of the research was the process of air pollutant emission occurring during welding, visible in the form of welding smoke. This smoke contains various pollutants that depend on many factors, including on the type of joined elements, welding method, type of welding equipment used. Depending on the particle size, welding smoke can be divided into:

- inhalable fraction (inhaled through the nose and mouth),
- respirable fraction with particle sizes smaller than 0.001 [mm].

The presence of oxygen in steel is harmful as it affects the type, content, form and decomposition of the oxides. In addition, it oxidizes (burns out) valuable alloying elements during the welding process, thus depleting the weld material. The presence of oxygen in steel increases its sensitivity to aging, delamination and brittleness cracking, and hot brittleness. In metals, oxygen is most often present in the form of oxides, including: FeO (dissolved in liquid steel up to 0.2%), Fe₂O₃, Fe₃O₄. The emission of oxides formed during welding goes both towards the weld, towards the slag (if it is formed) and towards the atmosphere. Thus, it poses a health risk to the welder, who gets these oxides into the body, whether through the respiratory system or the skin.

In order to protect the health of welding workers against all types of welding smokes, the legislator in Poland has defined the concentrations of hazardous substances that may be present in the air. These standards become the basis for the subsequent assessment of the exposure of the welding worker. They are included in the Regulation of the Minister of Family, Labor and Social Policy of June 12, 2018 on the maximum allowable concentrations and intensities of factors harmful to health in the work environment.

This paper presents the development of mathematical models of the emission of iron oxides formed during the welding process, based on the results of bench tests.

Materials and methodology of the research

In order to characterize the course of the pollutant emission process, bench tests were carried out. Tests of welding fillet welds using the MAG method (Metal Active Gas) of elements made of S235JR steel

with a thickness of 4 mm were made, with the use of 3 welding current values: 110 A, 130 A and 150 A. The chemical composition of the steel is given in table I.

Table I. Chemical composition of steel S235JR (% by weight) [10]

C	Mn	P	S	Fe	N	Cu
0.17	1.40	0.04	0.04	reszta	0.012	0.55

The following factors were adopted as constant factors in this study:

- type of material to be welded – structural non-alloy steel S235JR;
- shielding gas mixture – symbol M21 with Ar + 18% CO₂ content according to PN-EN ISO 14175;
- sheet thickness – 4 mm;
- type of weld – fillet;
- type of ventilation used – natural (gravity);
- electrode wire diameter – Ø1.2 [mm];
- used copper welding wire, classification EN400-G4Si1;
- electrode wire feed – 2.0 [m/min];
- arc voltage;
- welding device – semi-automatic welding machine by LINCOLN POWERTEC 305C;
- welding method – MAG type;
- sampling time.

The random, uncontrolled input factors – disturbances include, among others:

- contamination of welded surfaces;
- fluctuations in the flow of the shielding gas mixture;
- welding current drops;
- noise;
- optical radiation.

The air pollutant emission test during the welding process was carried out according to PN-Z-04008-7:2002 + Az 1:2004, *Air purity protection - Air sampling - Principles of air sampling in work places and interpretation of results*.

The measure of air pollution is amount of compounds deposited on the filters. The filters collected during the welder's work were subjected to physicochemical analysis. As a personal aspirator, the GILIAN GilAir3 device with a built-in flow stabilizer, pulsation damping system and flow disturbance indicator was used. Each time, before sampling, the aspirator was adjusted, and after sampling, the air flow in the aspirator was checked in the in-house laboratory.

In order to assess air pollution during the welding process, the following chemicals were tested:

- Iron oxides calculated as Fe – iron (III) oxide, iron (II) oxide, iron (II) iron (III) oxide – inhalable fraction;
- Iron oxides calculated as Fe – iron (III) oxide, iron (II) oxide, iron (II) iron (III) oxide – respirable fraction.

The abovementioned chemicals were identified based on PN-Z-04469:2015-10, *Air purity protection - Determination of iron oxides in respirable fraction of aerosol in workplaces by flame atomic absorption spectrometry*.

Results of the research

First, the emissions of iron oxides calculated as Fe – iron (III) oxide, iron (II) oxide, iron (II) iron (III) oxide – inhalable fraction were assessed. The data obtained are presented in table II. Then, in order to analyze the results, the data was implemented in the R program. A box plot was generated using the R program (Fig. 1) and the values of selected statistical parameters (Table III) were determined, i.e.:

- Min – minimum value;
- 1stQu. – lower (first) sample quartile (Q₁);
- Median – median ('middle value' Q₂);
- Mean – arithmetic mean;
- 3rdQu. – upper (third) sample quartile (Q₃);
- Max – maximum value;
- IQR – interquartile range;
- R – sample range;
- s – standard deviation;
- d₁ – standard deviation from the mean value.

Table II. Iron oxides – inhalable fraction [mg/m³]

No.	I=110 [A];	I=130 [A];	I=150 [A];
1.	1.17	1.27	1.54
2.	1.19	1.24	1.50
3.	1.15	1.29	1.49
4.	1.18	1.23	1.51
5.	1.16	1.30	1.54
6.	1.21	1.25	1.58
7.	1.20	1.29	1.55
8.	1.19	1.28	1.49
9.	1.18	1.24	1.54
10.	1.16	1.25	1.45

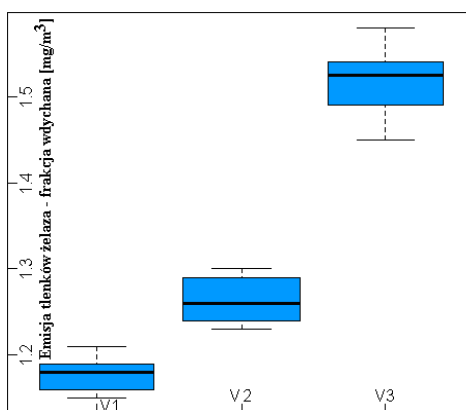


Fig. 1. A box plot generated in R software pertaining to the emission of iron oxides – inhalable fraction during the welding process for the welding current: V1 – I=110 A; V2 – I=130 A; V3 – I=150 A

Table III. A set of selected statistical parameters for measured iron oxides emissions of inhalable fraction during the welding process

Current I[A]	Min	1stQu.	Median	3rdQu.	Max	IQr	R	s	d1	Mean
110	1.15	1.163	1.180	1.190	1.21	0.0275	0.06	0.019	0.015	1.179
130	1.23	1.242	1.260	1.288	1.30	0.0450	0.07	0.025	0.022	1.264
150	1.45	1.492	1.525	1.540	1.58	0.0475	0.13	0.037	0.031	1.519

In the next stage, in order to generate mathematical models, the calculated average values of the emission of iron oxides – inhalable fraction were implemented into the R program and two polynomial models were built:

- model No. 1 (inhalable iron oxide – welding current) – first-order simple regression (Fig. 2);
- model No. 2 (inhalable iron oxide – welding current) – second degree curvilinear regression (Fig. 3).

After determining the values of the coefficients of the models, their diagnostics was performed in order to check their compliance with the measured results (Table IV). Then, from the set of models, one was selected that best suited the measured values of the emission of iron oxides – inhalable fraction (Fig. 4).

Table IV. Comparison of the calculated mean value of the emission of iron oxides - the inhalable fraction during the welding process with model values

Current I[A]	Model No. 1 [mg/m ³]	Model No. 2 [mg/m ³]	Mean [mg/m ³]
110	1.151	867.505	1.179
130	1.321	1205.433	1.264
150	1.491	1598.881	1.519

Model No. 1 (simple regression) for iron oxides – inhalable fraction is determined by the equation:

$$y=0.0085 \cdot x+0.2157 \quad (1)$$

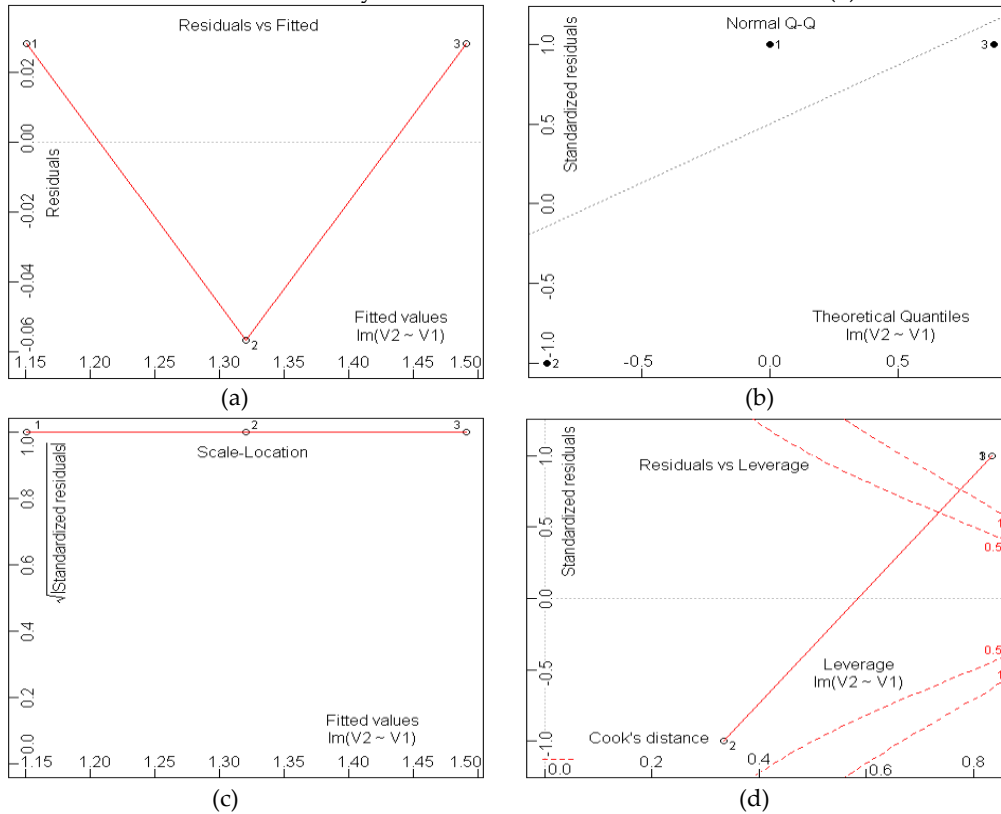


Fig. 2. Diagnostic charts for model No. 1 (iron oxides – inhalable fraction – welding current, simple regression)

Model No. 2 (second degree curvilinear regression) is determined by the equation:

$$y=0.0694 \cdot x^2+0.2404 \cdot x+1.3207 \quad (2)$$

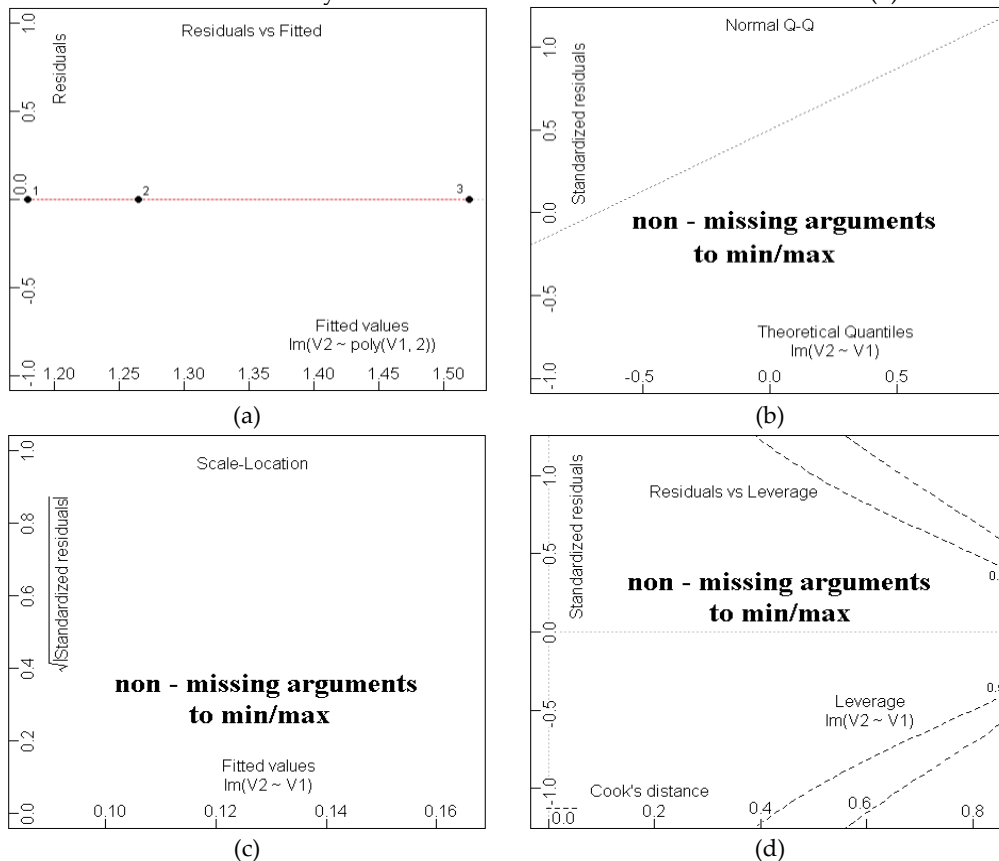


Fig. 3. Diagnostic charts for model No. 2 (iron oxides - inhalable fraction – welding current, second degree curvilinear regression)

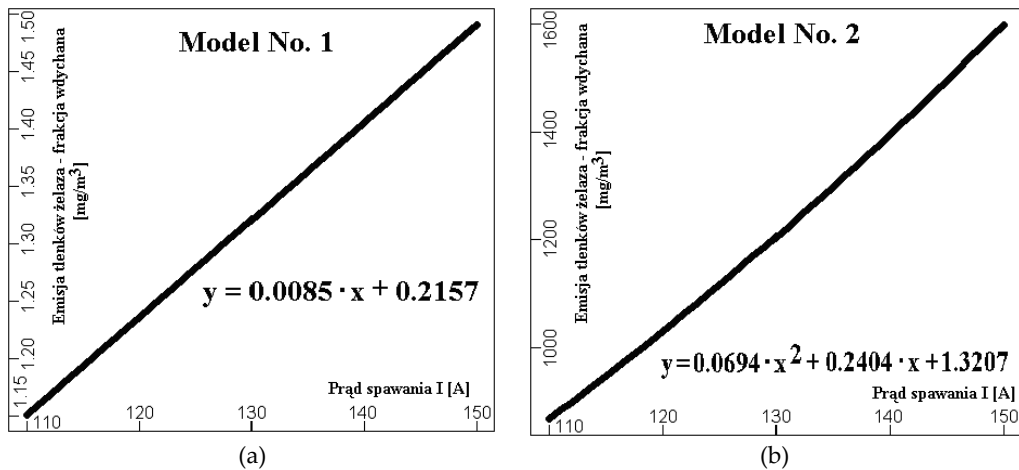


Fig. 4. Graph of the dependence of the emission of iron oxides - inhalable fraction on the welding current based on: a) model No. 1, b) model No. 2

The data on the emission of iron oxides - respirable fraction was similar. Data for the emission of iron oxides - respirable fraction collected during the tests are presented in table V, box plot in figure 5, values of selected statistical parameters in table VI. On the other hand, the polynomial models are presented in figures 6 and 7, and the comparison of the average emission of iron oxides - respirable fraction during the welding process with the model values is presented in table VII.

Table V. Iron oxides calculated as Fe-iron (III) oxide, iron (II) oxide, iron (II) iron (III) oxide – respirable fraction [mg/m³]

No.	I=110[A];	I=130[A];	I=150[A];
1.	0.93	1.07	1.38
2.	0.91	1.05	1.34
3.	0.90	1.11	1.35
4.	0.94	1.09	1.39
5.	0.95	1.13	1.37
6.	0.96	1.06	1.43
7.	0.94	1.10	1.40
8.	0.95	1.09	1.34
9.	0.95	1.06	1.42
10.	0.94	1.09	1.36

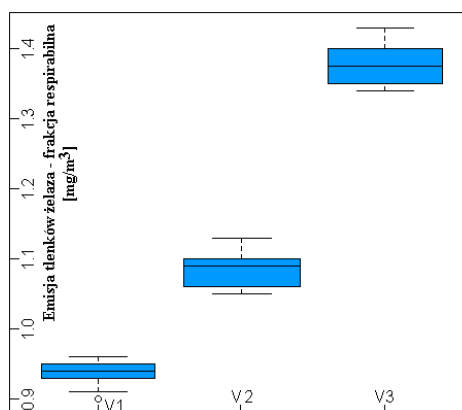


Fig. 5. A box plot generated in R software pertaining to the emission of iron oxides – respirable fraction during the welding process for the welding current: V1 – I=110 A; V2 – I=130 A; V3 – I=150 A

Table VI. A set of selected statistical parameters for measured iron oxides emissions of respirable fraction during the welding process

Current I[A]	Min	1stQu.	Median	3rdQu.	Max	IQR	R	s	d ₁	Mean
110	0.90	0.932	0.940	0.950	0.96	0.017	0.06	0.018	0.014	0.937
130	1.05	1.062	1.090	1.097	1.13	0.035	0.08	0.025	0.020	1.085
150	1.34	1.353	1.375	1.397	1.43	0.045	0.09	0.031	0.026	1.378

Model No. 1 (simple regression) for iron oxides – respirable fraction is determined by the equation:

$$y=0.01103 \cdot x-0.29992 \quad (3)$$

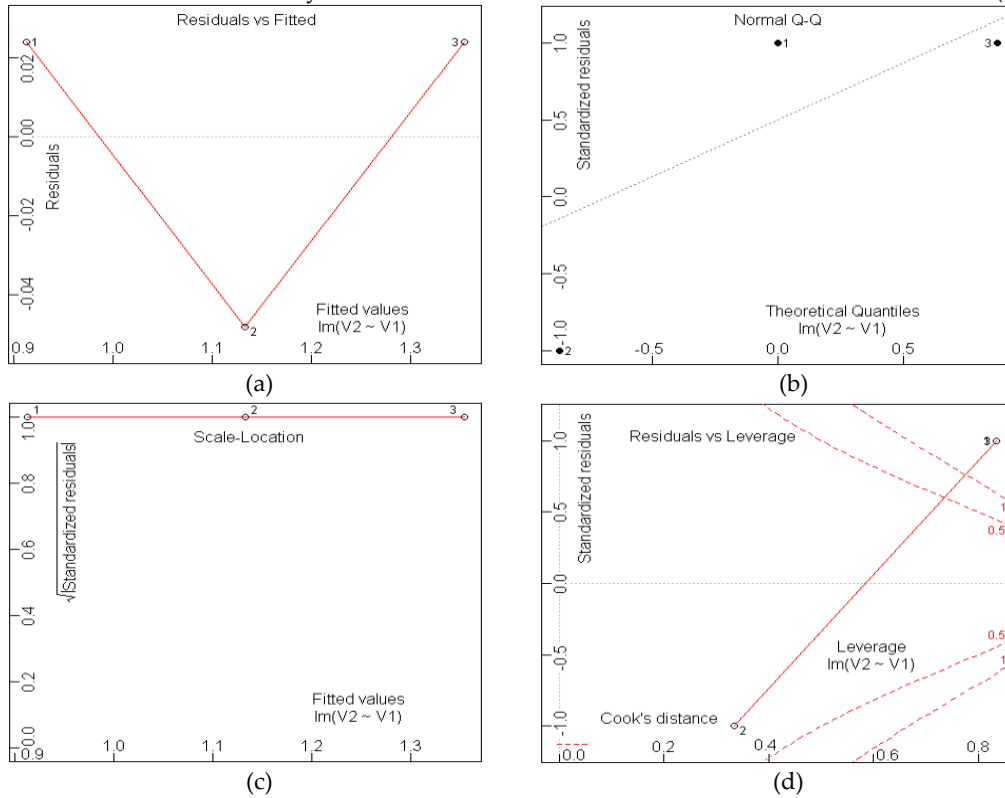


Fig. 7. Diagnostic charts for model No. 1 (iron oxides – respirable fraction – welding current)

Model No. 2 (second degree curvilinear regression) for iron oxides – respirable fraction is defined by the equation:

$$y=0.0592 \cdot x^2+0.3118 \cdot x+1.1333 \quad (4)$$

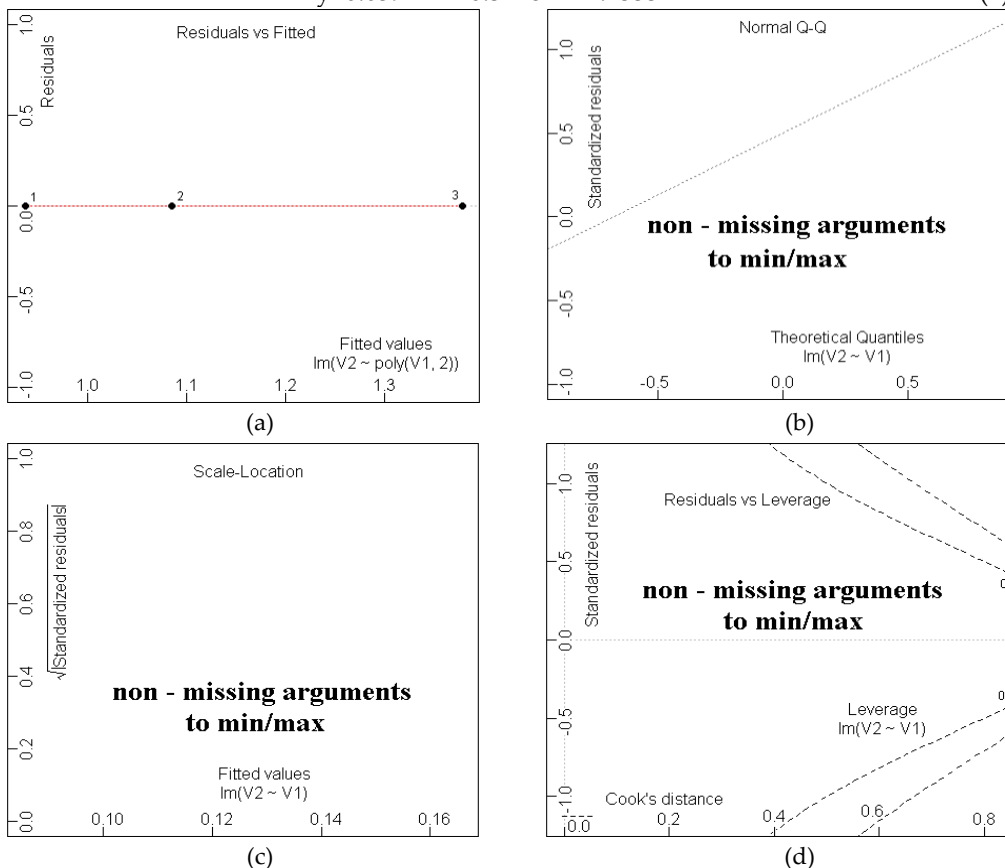


Fig. 8. Diagnostic charts for model No. 2 (iron oxides - respirable fraction – welding current)

Table VII. Comparison of the calculated mean value of the emission of iron oxides - the respirable fraction during the welding process with model values

Current I [A]	Model No. 1 [mg/m ³]	Model No. 2 [mg/m ³]	Mean [mg/m ³]
110	0.913	751.751	0.937
130	1.134	1042.147	1.085
150	1.355	1379.903	1.378

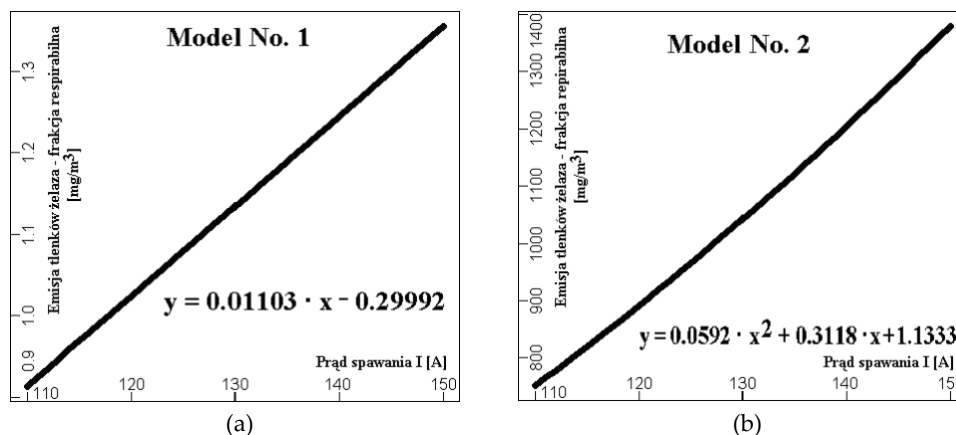


Fig. 9. Graph of the dependence of the emission of iron oxides - respirable fraction on the welding current based on: a) model No. 1, b) model No. 2

Summary

After analyzing the obtained test results concerning air pollutant emission during the welding process, the following conclusions can be drawn:

- with increasing welding current, the average value of the emission of iron oxide – inhalable fraction increases from 1.179 mg/m³ (for I=110A) to 1.519 mg/m³ (for I=150A);
- for the emission of iron oxides – inhalable fraction no outliers were recorded;
- with increasing welding current, the average value of the emission of iron oxide – respirable fraction increases from 0.937 mg/m³ (for I=110A) to 1.378 mg/m³ (for I=150A);
- for the emission of iron oxides – respirable fraction no outliers were recorded.

From the mathematical models presented here as adequate to the values of the obtained test results, one should assume:

- for iron oxides – inhalable fraction – model No. 1;
- for iron oxides – respirable fraction – model No. 1.

It should be noted, however, that, unfortunately, the above-mentioned models were built for a small data set (only for three welding current values).

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