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Effect of technological factors on diffusing hydrogen content in the weld deposit of rutile flux-cored wires

Abstract: The presence of diffusible hydrogen is one of the conditions for generation of cold cracks in welded joints and contributes to their porosity. In the work it was attempted to determine the gravity of selected technological factors in formation of diffusible hydrogen in weld metal what would make possible to forecast its content through changes of welding parameters. The statistical analysis of experimental results gathered during literature survey referring to the considered issue enabled to assess the gravity of the impact of seven factors on the amount of diffusible hydrogen in weld deposit of H10 class rutile flux-cored wire and to develop for them three forms of statistical models.

Keywords: cold cracks, diffusible hydrogen, rutile flux-cored wires;

Introduction

Presently MAG welding (135) is one of the most popular methods used in various industries. The use of flux cored wires can result in obtaining higher welding process efficiency and better joint quality. Flux-cored arc welding (136/138) combines the features of three arc welding processes, i.e. manual metal arc welding, semiautomatic solid wire welding and automatic submerged arc welding. The main advantage of this process is using a flux cored wire having a chemical composition which can be designed almost at will. An uncomplicated operation of devices and a relatively simple welding technique make the process usable in hard-to-access places and in difficult positions. In comparison with other welding methods it is possible to observe a continual increase in the use of processes based on flux cored wires [1]. In spite of many applications, flux cored arc welding has its restrictions due to requirements related to a content of diffusing hydrogen in a weld deposit. It is of particular importance while comparing this welding method with MMA welding and MAG welding (Fig. 1). It was ascertained [2,3] that in the case of smaller amounts of potential hydrogen the amount of diffusing hydrogen in a weld deposit made with a flux-cored wire is usually higher than in MIG/MAG methods [4].

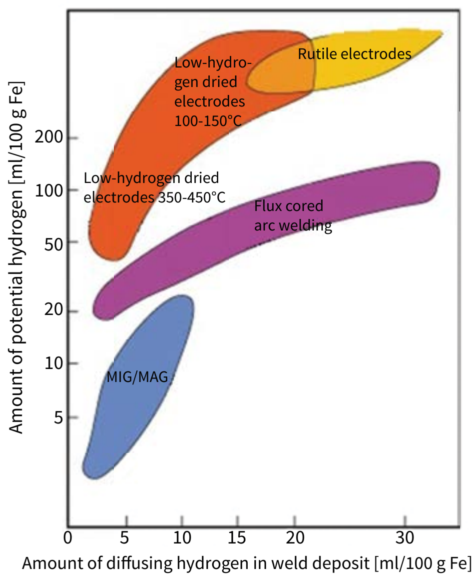

Fig. 1. Dependence between potential hydrogen and diffusing hydrogen for various welding methods [4]

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From a steel weldability point of view, the reduction of hydrogen amount in a weld deposit is convenient as it reduces susceptibility to cold cracking and porosity [3-6]. Increasingly popular welding with flux-cored wires is the reason for numerous research works aimed to improve steel weldability. Apart from eliminating hydrogen sources and technological methods of neutralising the detrimental influence of diffusing hydrogen (e.g. capturing diffusing hydrogen in weld deposits by adding rare-earth elements to the chemical composition of filler metals) one of the research directions worldwide is focused on the assessment of the possibility of controlling the amount of diffusing hydrogen by changing welding parameter values [2-4,7-18]. According to available reference publications, the amount of diffusing hydrogen in a welded joint can be significantly affected by many technological factors such as the type and amount of a shielding gas used, welding current, arc voltage, welding rate and exposed length of an electrode wire, environmental factors such as ambient pressure, temperature and humidity, as well as experimental factors such as a sampling methodology and sample dimensions [2-4, 7-18].

Until today, no complex methodology enabling forecasting the amount of diffusing hydrogen in a weld deposit generated in flux cored welding processes has been developed. This lack was the reason for attempting to develop statistical models describing this phenomenon. The research issue for a selected rutile flux-cored wire was solved experimentally [7] and by carrying out statistical analysis of data found in reference publications related to various grades of rutile flux-cored wires.

Statistical analyses

The purpose of the study was to qualitatively assess the effect of selected welding parameters and conditions on the amount of diffusing hydrogen in the weld deposit of H10 grade rutile flux-cored wires.

Input data for analyses were results published in reference publications concerning the determination of the amount of diffusing hydrogen in the weld deposit of various rutile flux-cored wire grades. Out of 55 results collected during the overview of reference publications [2-4,8-10,13,15], 29 results were selected as useful for statistical analyses due to the completeness of input data (experimental conditions and parameters).

Based on the analysis of reference publications and previous results it was ascertained that the group of input factors for statistical tests should include the type of shielding gas Rg (the amount of CO_2 in the shielding gas) [%], the consumption of the shielding gas Wg [l/min], welding current I [A], welding arc voltage U [V], welding rate Vsp [cm/min], welding linear energy El [kJ/cm] and the exposed length of the electrode wire Lw [mm].

The amount of diffusing hydrogen in the weld metal was determined by the glycerine method, the gas chromatography method and the high-temperature extraction method, which entailed their unification through conversion. The mercury method was selected as the standard method as it is recommended as a reference method [19-20].

The following dependences were used for conversions:

- from the glycerine method [21]:

$$H_{Drt}=1,123 \times H_{Dglic} + 3,934$$

- from the gas chromatography method [11]:

$$H_{Drt} = 1,2 \times [H_{chr.gaz.} - 0,27]$$

- from the high-temperature extraction method [22]:

$$H_{Drt} = 0,8698 \times H_{Dvhe} - 0,0542$$

where

- H_{Drt} – amount of diffusing hydrogen in a weld deposit determined using the mercury method [ml/100g Fe],
- H_{Dglic} – amount of diffusing hydrogen in a

weld deposit determined using the glycerine method [ml/100g Fe],
- $H_{chr.gaz}$ – amount of diffusing hydrogen in a weld deposit determined using the gas chromatography method [ml/100g Fe],
- H_{Dvhe} – amount of diffusing hydrogen in a weld deposit determined using the high-temperature extraction method [ml/100g Fe].

Table 1 presents the results of determining the amount of diffusing hydrogen in a weld deposit (put in order and converted into the mercury method indications) for carrying out statistical analysis.

Statistical analyses aimed at developing models H_D=f (Rg, Wg, I, U, Vsp, El, Lw) in linear and quadratic forms were carried out in a General Regression Models module of a Statistica package assuming a significance level of α = 0.05. The basic criterion adopted in order to compare dependences of a various number of factors was the value of the corrected determination factor R^2_{popr} [23, 24].

Table 1. Input data for statistical analyses

No.	Type of gas (amount of CO_2) Rg [%]	Gas consumption Wg [l/min]	Welding current I [A]	Arc voltage U [V]	Welding rate Vsp [cm/min]	Welding linear energy El [kJ/cm]	Exposed length of electrode wire Lw [mm]	Amount of diffusing hydrogen [ml/100g Fe]
1	100	17	288.00	28.30	75.00	10.87	11	9.53
2	100	17	284.00	28.30	75.00	10.72	11	10.53
3	100	17	288.00	28.30	75.00	10.87	11	8.68
4	25	30	105.83	21.44	9.00	25.21	15	4.37
5	25	30	112.33	21.35	9.00	26.65	15	5.38
6	25	30	135.80	20.89	9.00	31.52	15	5.66
7	25	30	146.65	20.92	9.00	34.09	15	5.96
8	25	30	161.10	20.36	9.00	36.44	15	6.27
9	25	30	177.77	19.87	9.00	39.25	15	7.48
10	25	30	196.70	20.24	9.00	44.24	15	7.61
11	25	30	200.75	19.56	9.00	43.63	15	7.88
12	25	18	280.00	30.00	66.67	12.60	15	20.13
13	25	18	300.00	30.00	66.67	13.50	15	16.89
14	25	18	320.00	30.00	66.67	14.40	15	16.29
15	25	18	280.00	30.00	66.67	12.60	20	17.49
16	25	18	300.00	30.00	66.67	13.50	20	15.21
17	25	18	320.00	30.00	66.67	14.40	20	15.45
18	25	18	280.00	30.00	66.67	12.60	25	14.13
19	25	18	300.00	30.00	66.67	13.50	25	12.93
20	25	18	320.00	30.00	66.67	14.40	25	12.33
21	100	18	280.00	30.00	66.67	12.60	15	13.77
22	100	18	300.00	30.00	66.67	13.50	15	14.97
23	100	18	320.00	30.00	66.67	14.40	15	15.09
24	100	18	280.00	30.00	66.67	12.60	20	11.13
25	100	18	300.00	30.00	66.67	13.50	20	12.57
26	100	18	320.00	30.00	66.67	14.40	20	12.93
27	100	18	280.00	30.00	66.67	12.60	25	9.69
28	100	18	300.00	30.00	66.67	13.50	25	9.81
29	100	18	320.00	30.00	66.67	14.40	25	10.05

The first analysis of the regression of test results presented in Table 1 was carried out using multiple reverse regression analysis (model I). The results of the analysis have been illustrated in a standardised effects Pareto chart (Fig. 2) revealing that all effects of the input factors of the model developed are statistically significant (exceed the red vertical line corresponding to the previously adopted significance level).

The following form of the regression equation was developed (model I):

$$H_{Drt}=381.4960-0.0457\times Rg-11.7543\times \times Wg+2.1866\times Vsp+0.1518\times \times El-0.4700\times Lw$$

where:
- H_{Drt} – amount of diffusing hydrogen in a weld deposit determined using the mercury method [ml/100g Fe],
- Rg – type of a shielding gas (the amount of CO_2 in the gas) [%],
- Wg – shielding gas consumption [l/min],
- Vsp – welding rate [cm/min],
- El – welding linear energy [kJ/cm],
- Lw – exposed length of electrode wire [mm].

A correlation coefficient R^2 between diffusing hydrogen amount values determined experimentally and those obtained through calculation equals 0.95, which means that the model explains 95% of the variability of experiment results. In turn, the value of a corrected correlation coefficient amounts to 0.94. Figure 3 presents the relation between the amount of diffusing hydrogen in a weld deposit determined experimentally (observed) and that calculated using model I (predicted).

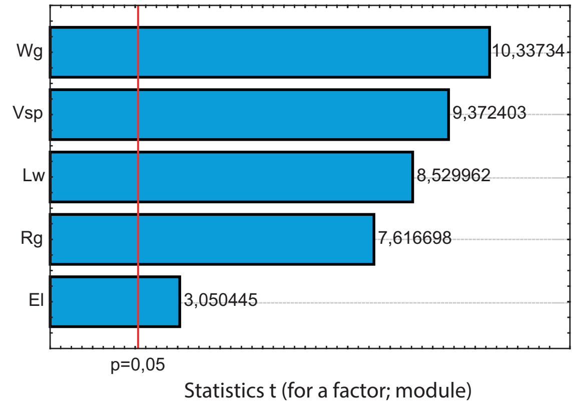


Fig. 2. Standardised effects Pareto chart (model I)

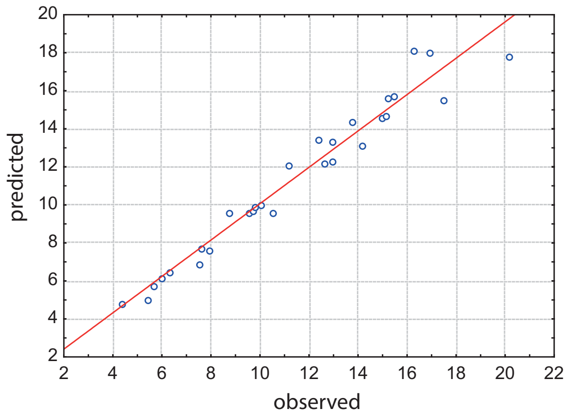


Fig. 3. Dependence between the amount of diffusing hydrogen in a weld deposit determined experimentally and amount calculated using model I

A condition for recognising the model as proper is the conformity of the distribution of raw residuals generated by the model (Fig. 4a) with the normal distribution [23,24]. Matching the distribution of raw residuals with the normal distribution was assessed using the

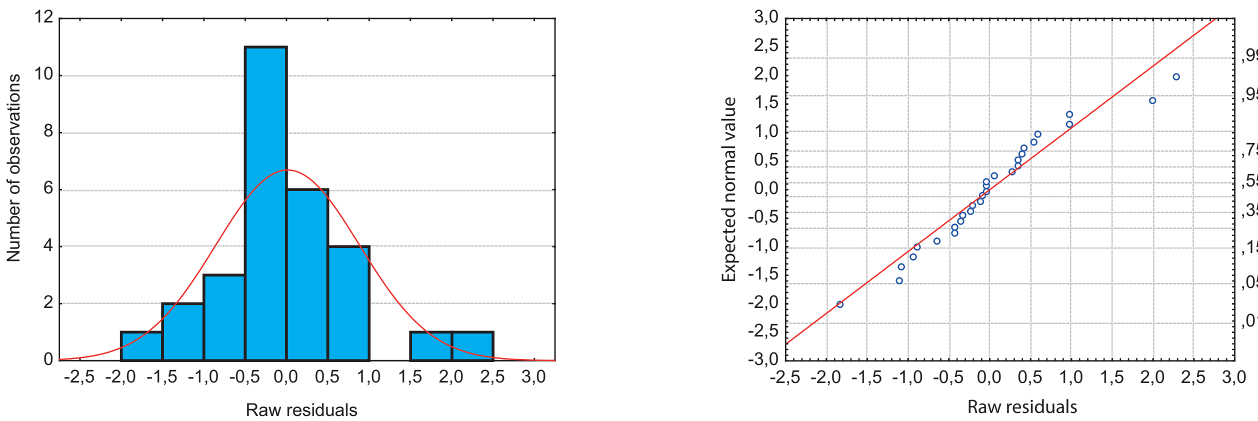


Fig. 4. a) Bar chart showing values of raw residuals (model I);
b) Line graph showing the normality of raw residuals (model I)

Shapiro–Wilk test and confirmed in a diagram of normality of residuals presented in Figure 4b. The residual values adhere to the line designating the normal distribution.

The next stage involved an attempt of developing the dependence H_D=f (Rg, Wg, I, U, Vsp, El, Lw) in the General Regression Models module, Polynomial Regression with the using the Best Subset Method. The standardise effects Pareto chart (Fig. 5) reveals that not all the effects of input factors are statistically significant. The analyses were repeated excluding the factor of the greatest value p (welding linear energy) in accordance with a procedure adopted for such analyses [23,24]. Model IIb (Fig. 6) was developed in a manner analogous to the methodology adopted in the previous analysis. In this model all the effects of input factors are statistically significant.

On the basis of the analysis of results the following form of the regression equation (model IIb) was adopted:

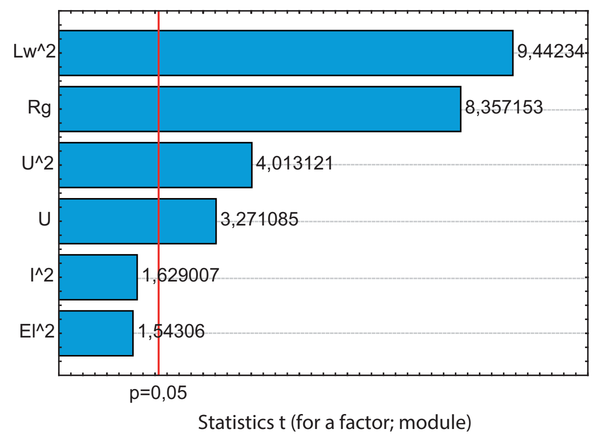


Fig. 5. Standardised effects Pareto chart (model IIa)

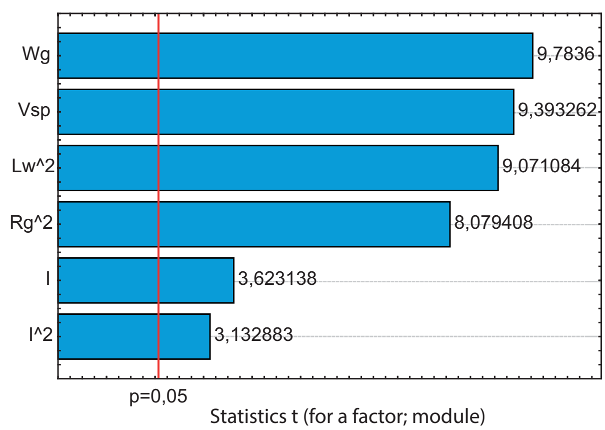


Fig. 6. Standardised effects Pareto chart (model IIb)

$$H_{Drt}=339.3829-0.0004\times Rg^2-10.6886\times \times Wg+0.0850\times I-0.0002\times I^2-2{,}0456\times \times Vsp+0.0117\times Lw^2$$

where:
- H_{Drt} – amount of diffusing hydrogen in a weld deposit determined using the mercury method [ml/100g Fe],
- Rg – type of shielding gas (the amount of CO_2 in the gas) [%],
- Wg – shielding gas consumption [l/min],
- I – welding current [A],
- Vsp – welding rate [cm/min],
- Lw – exposed length of electrode wire [mm].

The values of coefficients characterising the quality of matching the model with the experimental results are close to unity and amount to R=0.98, R^2=0.96, R^2_{popr}=0.95. This has been additionally illustrated in Figure 7 presenting the relationship between the values of diffusing hydrogen determined experimentally and those calculated using model IIb. The model is characterised by the conformity of the distribution of raw residuals with the normal distribution (Fig. 8).

Model III was developed using a progressive regression technique in the General Regression Models module, Polynomial Regression. In this case (Fig. 9) all the effects of input factors expressed in the model are statistically significant on the adopted level of significance.

On the basis of the analysis of results the following form of the regression equation (model

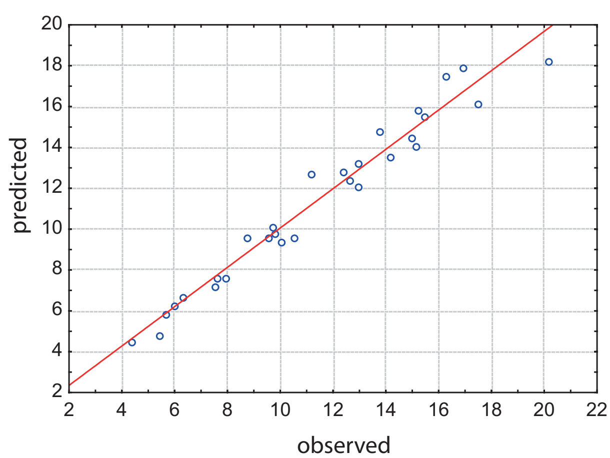


Fig. 7. Dependence between the amount of diffusing hydrogen in a weld deposit determined experimentally and amount calculated using model IIb

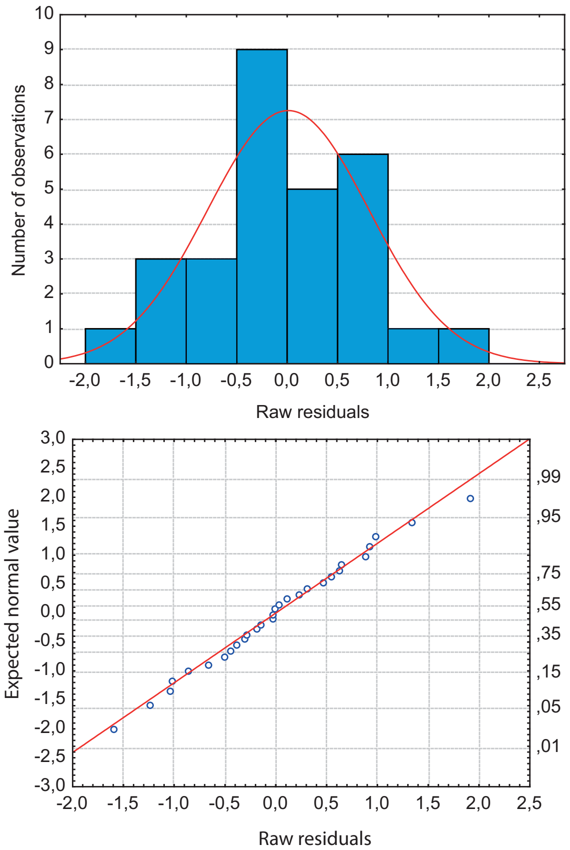


Fig. 8. a) Bar chart showing values of raw residuals (model IIb); b) Line graph showing the normality of raw residuals (model IIb)

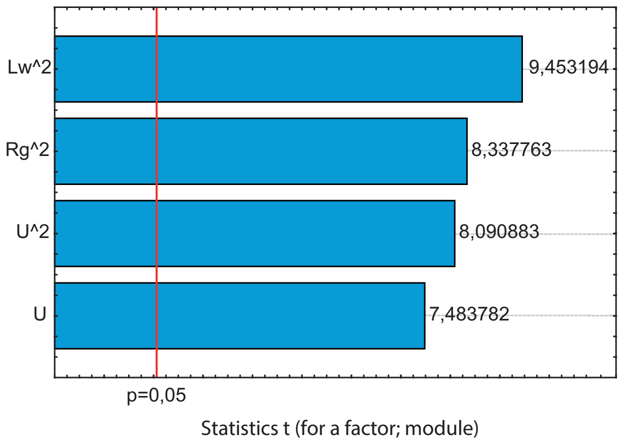


Fig. 9. Standardised effects Pareto chart (model III)

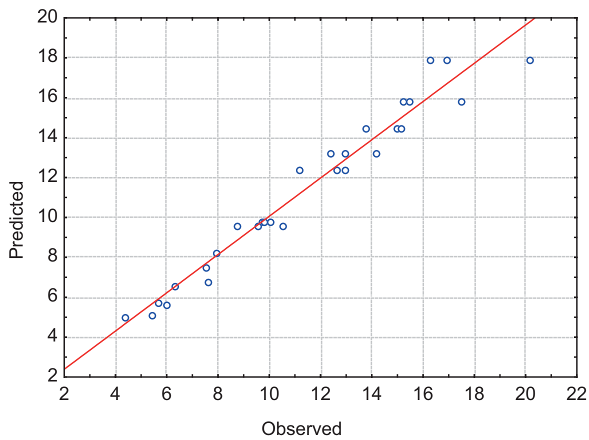


Fig. 10. Dependence between the amount of diffusing hydrogen in a weld deposit determined experimentally and amount calculated using model III

III) was adopted:

$$H_{Drt}=172.9846-0.0004\times Rg^2-14.2800\times U+0.3069\times U^2-0.012\times Lw^2$$

where

- H_{Drt} – amount of diffusing hydrogen in a weld deposit determined using the mercury method [ml/100g Fe],
- Rg – type of shielding gas (the amount of CO_2 in the gas) [%],
- U – arc voltage [V],
- Lw – exposed length of electrode wire [mm].

The dependence is statistically significant for high model quality values, which for model III are: R=0.97, R^2=0.95, R^2_{popr}=0.95 (see Figure 10). Also in this case the model developed is characterised by the conformity of the distribution of raw residuals with the normal distribution (Fig. 11).

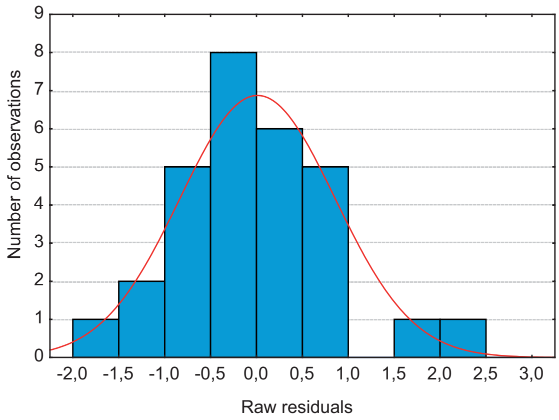
Summary

The statistical analysis of experimental results gathered during the overview of reference publications concerned with the issue under consideration made it possible to determine the significance of the influence of seven factors on the amount of diffusing hydrogen in the weld deposit of H10 class rutile flux cored wire, i.e. the type of shielding gas Rg, the consumption of a shielding gas Wg, welding current I, arc voltage U, welding rate Vsp, welding linear energy El and the exposed length of an electrode wire Lw.

The Statistica programme has been used to develop the general form models H_D=f (Rg, Wg, I, U, Vsp, El, Lw) fulfilling the assumptions of the least squares method (see Table 2).

The variability ranges of input factors determining the scope of usability of the models develop are the following (see Table 1):

- type of shielding gas (the amount of CO2) Rg [%]- [25 ÷ 100],
- shielding gas consumption Wg [l/min]- [17 ÷ 30],



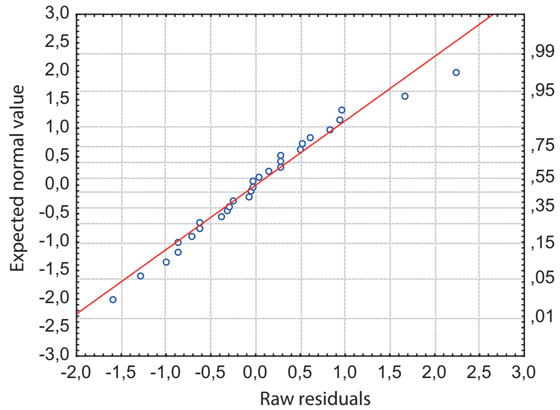


Fig. 11. a) Bar chart showing values of raw residuals (model III);
b) Line graph showing the normality of raw residuals (model III)

Table 2. Comparison of models developed

No.	Model	Model	R	R^2	R^2_{popr}
1	H_{Drt}=381.4960-0.0457×Rg-11.7543× × Wg+2.1866×Vsp+0.1518×El-0.4700×Lw	model I	0.977	0.956	0.946
2	H_{Drt}=339.3829-0.0004×Rg2-10.6886×Wg+0.0850× ×I-0.0002×I2-2.0456×Vsp+0.0117×Lw2	model II	0.981	0.962	0.952
3	H_{Drt}=172.9846-0.0004×Rg2-14.2800×U+0.3069× ×U2-0.012×Lw2	model III	0.979	0.958	0.951

- welding current I [A]-[105 ÷ 320],
- arc voltage U [V] - [19 ÷ 30],
- welding rate Vsp [cm/min] - [9 ÷ 75],
- welding linear energy El [kJ/cm] - [10 ÷ 44],
- exposed length of electrode wire Lw [mm] - [11 ÷ 25].

All the models are mathematically correct and characterised by high values of coefficients of matching with test results. Each of them can be used to forecast the amount of diffusing hydrogen in a weld deposit during welding with flux cored wires using parameters of the values restricted in the ranges indicated.

All the factors tested have a statistically significant effect on the amount of diffusing hydrogen. An increase in the carbon dioxide content in the shielding gas and in the consumption of a shielding gas causes a decrease in the amount of diffusing hydrogen in a weld deposit. A similar effect can be observed for an increase in the exposed length of an electrode wire. In turn, the effect of the remaining factors is reverse.

On the basis of the analyses conducted it is possible to state that one can significantly control the amount diffusing hydrogen in a weld deposit. However, the possibility of reducing the content of the latter is limited by the conditions necessary for obtaining proper quality joints, i.e. the lowest possible amount of welding imperfections ensures a proper weld shape and stable arc burning. The conclusions resulting from the statistical analyses have been confirmed by the results obtained experimentally [7].

Conclusions:

1. The study involved the statistical analysis of the effect of welding parameters on the amount of diffusing hydrogen in the weld deposit obtained with H10 class rutile flux cored wire using the analysis of the regression of data collected from reference publications.
2. It is possible to change the amount of diffusing hydrogen in a weld deposit by changing welding parameters tested. The range of controlling a sample hydriding degree is limited by the necessity of carrying out a welding

process in a stable way and by the necessity of obtaining required mechanical properties of joints.

3. The analytical models developed enable forecasting the amount of diffusing hydrogen in a weld deposit on the basis of known values of welding conditions and parameters, i.e. the type and consumption of a shielding gas, welding current, arc voltage, welding rate, welding linear energy and the exposed length of an electrode wire.

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