OPTIMIZATION OF TECHNOLOGICAL PARAMETERS OF SPOT RESISTANCE WELDING BY THE METHOD OF MULTIFACTOR DESIGN OF EXPERIMENTS

PUNKTKONTAKTMETINĀŠANAS TEHNOLOĢISKO PARAMETRU OPTIMIZĀCIJA, PIELIETOJOT EKSPERIMENTU DAUDZFAKTORU PLĀNOŠANAS METODI

I.Boyko, V.Kulakova, A.Filipov

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Introduction

Resistance welding is one of the oldest of the electric welding processes, which is in use today. Resistance spot welding is a commonly used resistance welding process. Resistance welding uses the application of electric current and mechanical pressure to create a weld between two pieces of metal. Weld electrodes conduct the electric current to the two pieces of metal as they are forged together. Accordingly, the weld is made by a combination of heat, pressure, and time. The required amount of time current flows in the joint is determined by material thickness and type, the amount of current flowing, and the cross-sectional area of the welding tip contact surfaces [1].

The resistance spot weld is unique because the actual weld nugget is formed internally with relation to the surface of the base metal. Figure 1 show a resistance spot weld nugget compared to a gas tungsten-arc (TIG) spot weld.

There are many approaches for the optimization of the technological parameters of welding process. In our opinion, for the known and applyied process the method of multifactor design of experiments (Box-Wilson method) could be usefull used [2].

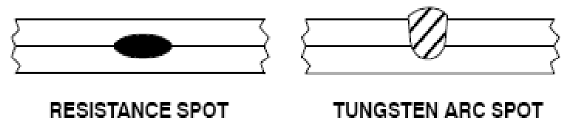

Fig.1. Comparison of the resistance and TIG spot welds [1]

Thus, for determination of an optimum welding parameters of welding of Fe- Ni-Co alloy (kovar) tube Ø1.2 mm with nickel foil 1.2 x 0.25 mm the mentioned method has been applied.

At the first stage on the basis of the experiments the mathematical model has been elaborated.

As a parameter of optimization Y the tearing strength of welded connection P (N) was accepted. Restrictions of optimization were: settling value s and presence of metal splashing.

On the basis of preliminary optimization [3] for study of welding parameters influence on welding process the following factors were chosen: x_1 - pressing force on electrodes F_e, N; x_2 - capacity of working condensers C, μF; x_3 - voltage of working condensers U_C, V. The transformation coefficient K_T=80 - const.

The lineal mathematical model looks like:

$$Y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 . \qquad (1)$$

On the basis of preliminary optimization the local area of definition of the factors has been established. It was decided to vary each of the factors at two levels. The variability intervals are shown in Table 1.

For definition of four coefficients of the regression equation the complete factorial experiment 2^3 was carried out, the design matrix contains 8 experiments (Table 2).

At the first stage of a steep ascent the mixed paired interactions were ignored, because the equation was adequate. For compensation of influence of random errors and for discovery of more precise results, experiment at uniform doubling of five parallel experiments was carried out.

Design matrix and results of experiments are shown in Table 2.

Table 1

Levels and variability intervals of factors

Factors	Levels of factors			Variability intervals
	low –1	zero 0	upper +1	
x_1, N (pressing force on electrodes)	18	20	22	2
x_2, μF (capacity of working condensers)	325	350	375	25
x_3, V (voltage of working condensers)	300	325	350	25

Table 2

Design matrix and results of experiments

Nr.	Order of implementation	x_0	F_e	C	U_C	$\overline{Y}$	$S^2_{Y_i}$	$\hat{Y}$	$\left(\overline{Y}-\hat{Y}\right)^2$
			x_1	x_2	x_3				
1	7	+1	–1	–1	+1	109.3	3.24	109.16	0.02
2	2	+1	+1	–1	–1	40.1	2.25	39.59	0.26
3	8	+1	–1	+1	–1	98.3	4.41	97.38	0.85
4	3	+1	+1	+1	+1	67.9	10.30	66.13	3.13
5	1	+1	–1	–1	–1	61.1	2.10	59.44	2.76
6	4	+1	+1	–1	+1	79.8	5.29	78.55	1.56
7	5	+1	–1	+1	+1	124.2	5.76	123.61	0.35
8	6	+1	+1	+1	–1	56.2	2.82	55.81	0.15
Regression coefficient b_i		79.61	–18.61	7.04	15.69	$\sum S^2_{Y_i}=36.17$; $\sum_{i=1}^{N}\left(\overline{Y}-\hat{Y}\right)^2=9.08$			

Dispersion of experiments

Row average value of optimization parameter $\overline{Y}$ was determinated as:

$$\overline{Y}=\frac{\sum_{i=1}^{n} Y_i}{n}, \qquad (2)$$

where n – number of parallel experiments; Y_i – result of each experiment.

Row average value of dispersion of parallel experiments was determinated as:

$$S^2_{Y_i}=\frac{\sum_{i=1}^{n}\left(Y_i-\overline{Y}\right)^2}{n-1}. \qquad (3)$$

Then the Kohren criterion was calculated:

$$G_{calc} = \frac{S^2_{Y i\,max}}{\sum_{i=1}^{N} S^2_{Y_i}} = \frac{10.30}{36.17} = 0.285\,, \qquad (4)$$

where $S^2_{Y_{i\,max}}$ - maximal dispersion in series; $\sum_{i=1}^{N} S^2_{Y_i}$ - sum of all dispersions; N – number of experiments in design matrix. At significance level α = 0.05 and number of degree of freedom $f = n - 1 = 4$ (number of experiments N = 8) the tabulated value of Kohren criterion is G_t = (0.05; 4; 8) = 0.391. Since a calculated Kohren criterion is smaller than tabulated value it is safe to say, that the series of dispersions are homogeneous.

In this case the dispersion of experiment was calculated as follows:

$$S^2_Y = \frac{\sum_{i=1}^{N}\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}{N(n-1)} = \frac{36.17}{8} = 4.52\,, \qquad (5)$$

where $f_1 = N(n-1) = 32$ – number of degree of freedom.

Regression coefficients

For calculation of regression coefficients following expressions where used:

$$b_0 = \frac{\sum_{i=1}^{N} \overline{Y}}{N}; \quad b_i = \frac{\sum_{i=1}^{N} Y_i x_i}{N}. \qquad (6)$$

Consequently the values of coefficients are: b_0 = 79.61; b_1 = –18.61; b_2 = 7.04; b_3 = 15.69. Thus, the mathematical model of process is polynomial of first degree:

$$Y = 79.61 - 18.61x_1 + 7.04x_2 + 15.69x_3. \qquad (7)$$

Model verification

The dispersion of inadequacy were calculated as:

$$S^2_{non-validity} = \frac{n \cdot \sum_{i=1}^{N}\left(\overline{Y} - \hat{Y}\right)^2}{f_2}\,, \qquad (8)$$

where $f_2 = N - k = 8 - 4 = 4$ - number of degree of freedom, $k = 4$ - number of regression coefficients in model. Thus,

$$S^2_{non-validity} = \frac{5 \cdot 9.08}{4} = 11.35\,. \qquad (9)$$

Hypothesis about model adequacy was verified by Fisher F-criterion. At α = 0,05, $f_1 = 32$ and $f_2 = 4$ the Fisher F-criterion is equal to a F_{table}(0.05; 4; 32) = 2.69.

Calculated value of F-criterion is:

$$F_{calc}(4;32) = \frac{S^2_{non-validity}}{S^2_Y} = \frac{11.35}{4.52} = 2.51\,. \qquad (10)$$

Since F_{calc}(4; 32) = 2.51 < 2.69 = F_{table}(0.05; 4; 32), we assumed that model is adequate at 5% significance level.

Analysis of model

As a result of the analysis of received mathematical model (7) has been established, that in the chosen variability intervals of factors the greatest influence on parameter of optimization (the tearing strength of welded joint) has

- pressing force on electrodes (x_1) and
- voltage of condensers (x_3), but capacity of working condensers (x_2) – least of all.

For increasing of optimization parameter level it is necessary to increase values of the factors x_2 (C) and x_3 (U_C), and to reduce value of the factor x_1 (F_e), that is not in conflict with basics physics of process.

Calculation of steep ascent on response surface

Steep ascent was beginning from the zero point (zero factors values): x_1 = 20; x_2 = 350; x_3 =

325. Step for factor x_1 was taken equal to: $\Delta_1 = -0.5$. Steps for other factors were calculated as follows:

$$\frac{b_1 \cdot \Delta x_1}{b_2 \cdot \Delta x_2} = \frac{\Delta_1}{\Delta_2};$$

$$\Delta_2 = \frac{7.04 \cdot 25 \cdot (-0.5)}{(-18.61) \cdot 2} = 2.36 \approx 2; \qquad (11)$$

$$\frac{b_1 \cdot \Delta x_1}{b_3 \cdot \Delta x_3} = \frac{\Delta_1}{\Delta_3};$$

$$\Delta_3 = \frac{15.69 \cdot 25 \cdot (-0.5)}{(-18.61) \cdot 2} = 5.27 \approx 5. \qquad (12)$$

Then steps were consequently added to factors ("mind experiments"), corresponding series of experiments are shown in Table 3.

The implementation (calculation of a steep ascent) has shown the best result on tearing strength in experiment Nr.4: P = 128.5 N, which is almost equal to tearing strength of nickel foil (130 N). Hence, the found welding conditions are in the field of an optimum. Thus, have received the qualitative weld without metal splashing and with an allowable final settling value s = 0.054 mm.

Table 3

Calculation of steep ascent

Factors values	Order of implementation	**x_1**	**x_2**	**x_3**	**$\bar{Y}$**
Zero level		20	350	325	—
Coefficient b_i		– 18.61	7.04	15.69	—
Variability interval		2	25	25	—
$b_i \Delta x_i$		– 37.22	176	392.25	—
Step		– 0.5	2.36	5.27	—
Round step		– 0.5	2	5	—
Mind experiments					
1	1	19.5	352	330	97.6
2	5	19	354	335	112.8
3	2	18.5	356	340	102.6
4	4	18	358	345	128.5
5	3	17.5	360	350	117.4

Conclusions

As a result of optimization of welding process by the method of multifactor design of experiments the regression equation was obtained. Received mathematical model adequately describes the gradient motion to the optimal area of factors and degree of influence of each factor on optimization parameter as well. However, physics of influence of factors on the heating process, deformation and weld formation process was not disclosed. It must be mentioned that such disclosure is not a goal of this method. Therefore it could be useful to investigate the influence of technological parameters on the weld formation process and this is an objective of estimated research.

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Irina Boyko, Dr.sc.ing.
Docent
Riga Technical University, Mechanical Engineering Institute
Address: Ezermalas Str. 6k, LV-1006, Riga, Latvia
Phone: +371 67089701, Fax: +371 67089739
e-mail: irinaboyko@inbox.lv

Vera Kulakova, M.sc.ing.
Riga Technical University, Mechanical Engineering Institute
Address: Ezermalas Str. 6k, LV-1006, Riga, Latvia
Phone: +371 67089701, Fax: +371 67089739
e-mail: v.mensk@gmail.com

Alexander Filipov, Dr.sc.ing.
Head of the Research Laboratory of Automation of Welding Processes
Riga Technical University, Mechanical Engineering Institute
Address: Ezermalas Str. 6k, LV-1006, Riga, Latvia
Phone: +371 67089701, Fax: +371 67089739
e-mail: weld5@inbox.lv

Boiko I., Kulakova V., Fiļipovs A. Punktkontaktmetināšanas tehnoloģisko parametru optimizācija, pielietojot eksperimentu daudzfaktoru plānošanas metodi
Šis raksts ir veltīts punktkontaktmetināšanas tehnoloģisko parametru optimizācijai, pielietojot eksperimentu daudzfaktoru plānošanas metodi. Ir zināmas vairākas pieejas metināšanas procesu tehnoloģisko parametru optimizācijai, taču pēc autoru domām eksperimentu daudzfaktoru plānošanas metode (Boka-Vilsona metode) ir īpaši lietderīga iepriekš izstrādāto procesu optimālo parametru precizēšanā.
Iegūta matemātiska modeļa analīzes rezultātā tika noteikts, kā faktoru izvēlēto variēšanas intervālos vislielāk uz optimizācijas parametru (metināšanas savienojuma stiprību stiepē) ietekmē saspiešanas spēks elektrodos un spriegums kondensatoros, vismazāk – darba kondensatoru kapacitāte. Iegūtais matemātiskais modelis adekvāti apraksta gradienta kustību pie faktoru optimāla lauka, kā arī katra faktora ietekmes pakāpi uz optimizācijas parametru. Plānos ir izpētīt arī tehnoloģisko parametru ietekmi uz metināta savienojuma formēšanas procesu.

Boyko I., Kulakova V., Filipov A. Optimization of technological parameters of spot resistance welding by the method of multifactor design of experiments
This article is devoted to the optimization of technological parametrs of spot resistance welding by the method of multifactor design of experiments (Box-Wilson method). There are many approaches for the optimization of the technological parameters of welding process. In our opinion, for the known and applyied process the method of multifactor design of experiments could be usefull used.
As a result of the analysis of received mathematical model has been established, that in the chosen variability intervals of factors the greatest influence on parameter of optimization (the tearing strength of welded joint) has pressing force on electrodes and voltage of condensers, but capacity of working

condensers – least of all. Received mathematical model adequately describes the gradient motion to the optimal area of factors and degree of influence of each factor on optimization parameter as well. It could be useful to investigate the influence of technological parameters on the weld formation process and this is an objective of estimated research.

Бойко И., Кулакова В., Филиппов А.
Оптимизация технологических параметров точечной контактной сварки при помощи метода многофакторного планирования эксперимента

Статья посвящена оптимизации технологических параметров точечной контактной сварки при помощи метода многофакторного планирования эксперимента (крутое восхождение Бокса-Уилсона).
Известно большое количество подходов в оптимизации технологических параметров сварки, однако по мнению авторов метод Бокса-Уилсона является особенно полезным при уточнении оптимальных параметров ранее разработанных процессов.
В результате анализа полученного уравнения регрессии было установлено, что в выбранных интервалах изменения факторов на параметр оптимизации (прочность сварного соединения на отрыв) наименьшее влияние оказывает ёмкость рабочих конденсаторов. Наибольшее влияние оказывает усилие сжатия на электродах и напряжение зарядки конденсаторов. Полученная математическая модель адекватно описывают движение по градиенту к оптимальной области факторов и отражает степень влияния каждого фактора на параметр оптимизации. Планируется провести также исследования влияния технологических параметров на процесс образования сварных соединений.