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Optimizing the control process parameters for the induction soldering of aluminium alloy waveguide paths[1]

V S Tynchenko, A V Murygin, V E Petrenko, O A Emilova, A N Bocharov
Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russian Federation

E-mail: vadimond@mail.ru

Abstract. The paper describes the problem of selecting the optimal initial values of algorithm parameters for the process of the induction soldering of aluminium alloy waveguide paths. The authors consider some factors influencing the quality of waveguide soldered joint elements. These factors depend on the correct choice of initial values for control parameters. The problem of optimizing such parameters for further analytical and numerical studies is researched by authors. For solving the stated task, the random search method is selected, allowing for an acceptable field study within the stated time to solve the problem of control optimization with the level of accuracy required by the technological process. Therefore, optimal initial values of the induction soldering technological process were found for three sizes of waveguide tubes and flanges.

1. Introduction

The induction soldering of aluminium alloy waveguide paths is a high-tech process that requires complex modern automated equipment and the highly accurate refinement of parameter values [1, 2, 3]. The main difficulties consist in the diversity of the possible sizes of products, and also in the need to fine-tune the technological process for each of them, as well as in the presence of an inductor with a complex profile [4, 5, 6, 7].

The authors of this work implemented a set of automated equipment, allowing the process of soldering waveguide paths to be performed. This process is controlled by the preinstallation of a gap by means of an “inductor-flange” with a margin of error of no more than 0.2 mm, and for each product empirical values are required matching the clearance. Then the technological process of soldering is launched in the control system, during which the generator power is regulated in accordance with the established heating rate and stabilization mode settings when the melting temperature of the solder is reached. [8, 9, 10]

However, if such a control system is used, there is the problem of refining the clearance, whereby even small deviations can lead to breaches of the conditions for obtaining high-quality connections. As a result, the process management system operator is forced to adjust

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the clearance of the inductor-flange, thereby redistributing the currents induced in the workpiece in the following situations [11]:

- if the process reaches the melting temperature of the solder leading to the convergence of the process;
- if the process encounters a situation whereby it is obvious that there is a significant deviation from the normal operation of the system;
- failover process.

In consequence, the human factor influencing the quality of finished product is crucial, and in this way, the percentage of defects depends on the experience of the induction soldering process operator. This results in the need to modernize the automated equipment in order to exclude the influence of the human factor, to accelerate the technological process and to improve the repeatability of the process.

2. Description of the specifics of the waveguide path soldering process

After modernizing the equipment and performing preliminary tests, there arose the problem of optimizing the process with the new increased complexity of the system. The insertion of a second control circuit that changes the position of the workpiece relative to the inductor window during the soldering process made the system multiply connected, nonlinear and nonstationary. This issue was resolved through the development of a logical control regulator, which allowed the soldering process to be controlled regardless of the size of the soldered element with a wide range of technological process initial parameters.

Initial launch parameters have become crucial in ensuring the required regulation performance of the system, as the regulator settings are selected in such a way as to guarantee proper control of the soldering process with elements of any size. Such an influence corresponds to a high level of dependence on the initial temperature distribution tubes and flange/coupling, due to the high threshold of the perception pyrometric temperature sensor, which is 300 degrees Celsius.

However, a non-optimized soldering process allows us to get soldered connections by reducing the starting power, which significantly increases the time the process takes, diminishing the electromagnetic characteristics of the finished product. Also, a strong variation of the initial temperature distribution between the elements of the soldered product can have such values, under which subsequent regulation fails to reduce the heating process to the required technological parameters for the subsequent limited plot.

3. The problem of choosing the control parameters

The complexity of the algorithm in the automated system with a second control circuit leads to the appearance of additional control unit settings. The heating process quality is significantly influenced by initial control system settings, such as:

- the initial power fed to the inductor;
- the initial position of the workpiece relative to the inductor window.

When using a single-loop control, the starting power was set to the maximum possible for the generator, because reducing the temperature difference between the waveguide elements was not the goal of the regulation, and the distance between the waveguide and inductor window was constant throughout the technological process of soldering. Now with double-circuit control the aim is to improve the quality of the technological process by eliminating temperature differences between elements of soldered product. Due to this there is a problem of choosing the initial value of the power supplied to the inductor, as well as the clearance between the workpiece and the inductor window.

In a separate work, the authors proposed and tested methods and algorithms to control the waveguide path induction soldering process using a two-circuit control system for the temperature of the elements of the product to be soldered and the gap between the inductor window and the connecting flange/coupling.

The present study task is to select the initial values of the studied parameters of the control system.

To solve such a problem, it is necessary to determine the correlation between the adoption of parameters of boundary values and the resulting influence on the heating process and the quality of the soldered connection.

Table 1 summarizes the results of experimental research on the initial parameter values.

An example that illustrates the implications of choosing a high initial value for the power generator is presented in Figure 1.

In the process presented in Figure 1, a high weakly damped oscillation occurs in the control process. Also, there are examples of swelling and melting of the main material.

Table 1. Correspondence of control system parameter initial values and their influence on the quality of the induction soldering technological process

Parameter	Meaning	Consequences
Generator power	High	Local overheating of the product, swelling and melting of the main material (for couplings). A high initial spread of the temperature distribution of the product elements. The need to search for the initial position and high-precision positioning of the workpiece relative to the inductor window to obtain an even distribution of heating between the elements of the product.
	Low	Time delays in the process. Reductions in the efficiency of the generator due to heat loss during convection and self-heating of the inductor. Ambiguity in the choice of the initial position of the workpiece to the inductor window. When registering temperatures, the flange is superheated, which subsequently leads to its melting.
The gap between the inductor and the product	High	Overheating of the tube outside the pyrometer temperature control zone. An essentially uneven temperature field across the product section. Poor warming of the flange, leading to a tightening of the soldering process. Long-term transient when regulating. The probability of reflow of the tube’s top and local burns of the main material at the end of the soldering process.
	Low	Overheating of the flange in the preheating stage, resulting in a long transient during adjustment. High probability of flashing at the end of the soldering process.

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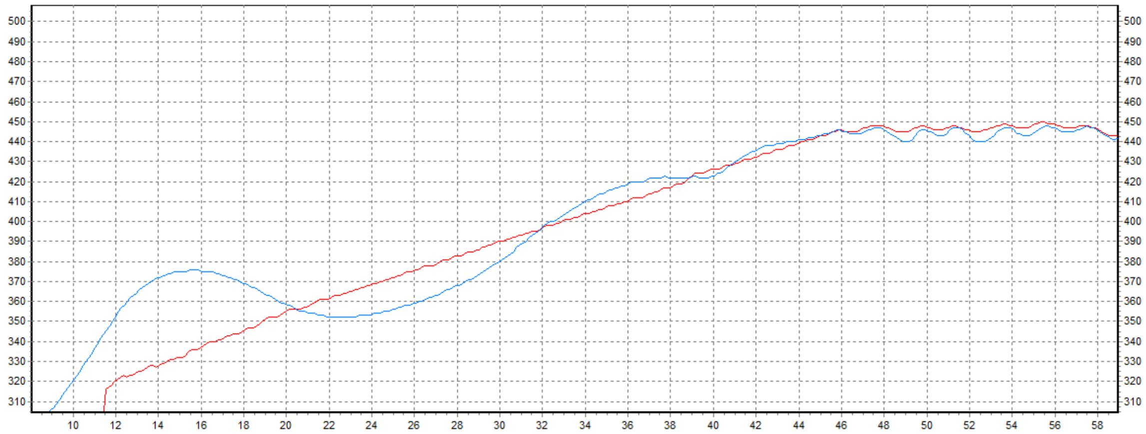

Figure 1. Temperature charts of elements with an initial high power value of the power generator
Red line – tube temperature, blue line - temperature of the flange.
Y axis - temperature, X axis - time.

Examples to illustrate the implications of choosing extreme values for the gap between the inductor and the product are presented in Figures 2 and 3.

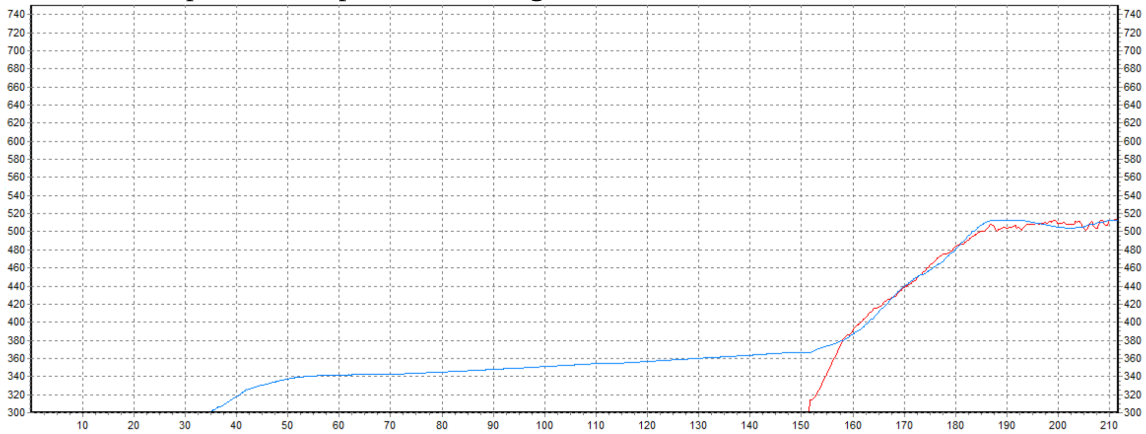

Figure 2. Graph showing the heating tube-flange (58 × 25 mm) with the initial gap between the inductor and flange of 3 mm
Red line – tube temperature, blue line - temperature of the flange.
Y axis - temperature, X axis - time.

In the process presented in Fig. 2 can be seen significant overheating of the flange relative to the tube at the beginning of the technological process. The total time for the soldering process is protracted. In the area of solder melting (520-540 Celsius degrees), there is a weakly damped oscillation. On the product elements occur swelling and melting of the core material.

In the process presented in Fig. 3 can be seen significant overheating of the tube relative to the flange at the beginning of the technological process. The total time for the soldering process is protracted. On the process stabilizing phase (solder melting point) the heat distribution in the tube leads to it being impossible for the regulator to reduce the difference in product element temperatures.

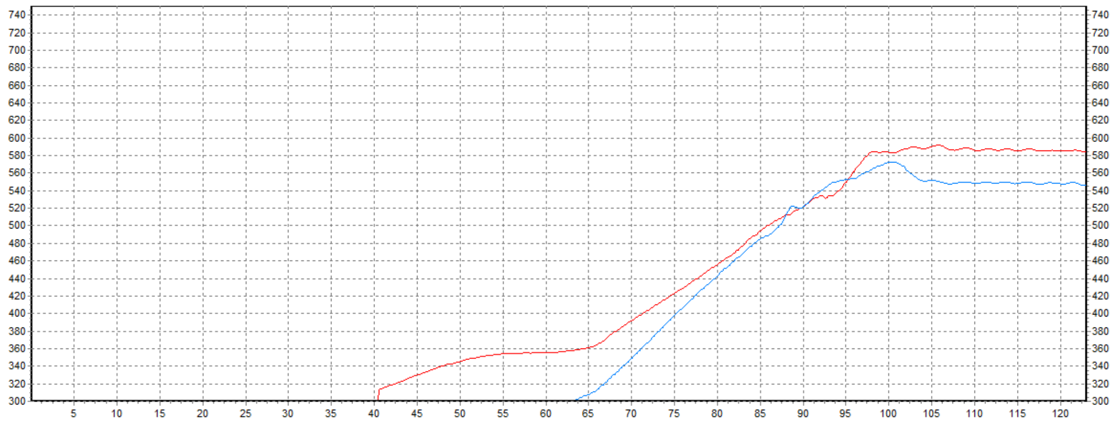

Figure 3. Graph showing the heating tube-flange (58 × 25 mm) with the initial gap between the inductor and flange of 9 mm
Red line – tube temperature, blue line - temperature of the flange.
Y axis - temperature, X axis - time.

4. The estimation of the induction soldering control quality

The need to select optimal values for the control system initial parameters can be explained by such reasons as:

- flux activity time after its meltdown (490-520 degrees Celsius) is about 10 seconds, which leads to the necessity of the heating speed being at a minimum of 8 degrees Celsius per second from the flux melting until the solder melting;
- selecting the workpiece from an incorrect starting position relative to the inductor window, the control system fails to reduce the difference between temperatures of the product elements according to the required technological standards;
- proper selection of the control process initial parameters allows quality soldered connections of waveguide elements to be formed within a reasonable time.

Quality control can be estimated as the integral of the tube and flange/coupling temperature difference function (1):

$$f(W,h) = \int_0^\infty \left(T_{fl}(t,W,h) - T_{tb}(t,W,h)\right) dt \rightarrow \min_{\substack{W>0 \\ h>0}} \quad (1)$$

where W is the generator power;
h is the gap size;
$T_{fl}(t,W,h)$ is the flange/coupling temperature;
$T_{tb}(t,W,h)$ is the tube temperature.

To use numerical optimization methods instead of the target function (1), the average quadratic deviation between the temperatures of the heated elements can be employed.

Then the target feature that provides the reduction of the difference in temperature of soldered elements takes the form (2):

$$F(W,h) = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(T_{fl}^{i} - T_{tb}^{i}\right)^2} \rightarrow \min_{\substack{W>0\\h>0}} \qquad (2)$$

where W is the generator power;

h is the size of the gap;

n is the number of function evaluations;

T_{fl}^{i} is the measured temperature of the flange/coupling at the i-th point of the technological process;

T_{tb}^{i} is the measured temperature of the tube at the i-th point of the technological process.

5. Methods of problem solving

There are a variety of methods to solve the optimization task:

1) direct methods;
2) gradient methods;
3) Newton's methods.

Because neither the task of optimizing the soldering technological process parameters, nor the research object has a well-defined mathematical model, and the value of the function is obtained by conducting full-scale welding experiments on the product test samples, only methods belonging to the first group, namely direct methods, can be used to solve the optimization problem of such a process, those that use only information about the target function values.

The problem of this study has several characteristic features:

1) low dimensionality of the search space;
2) small uncertainty intervals;
3) optimized parameters with low discreteness;
4) a limited number of possible target function calculations due to the high cost of the full-scale experiment.

Among the group of direct methods, the most commonly used are [12]:

1) the uniform search method;
2) the Golden section method;
3) the Fibonacci method;
4) the random search method in its different variations;
5) Powell's method;
6) the method of Hooke-Jeeves;
7) the method of Nelder-Mead.

The first three methods find wide application in problems of one-parameter optimization, however, are poorly suited to multidimensional cases.

The methods of Powell, Hooke-Jeeves and Nelder-Mead require quite a large amount of target function computing to implement at least one iteration of the algorithm, which limits their application in the field of experimental research. The random search method is widely used in practical research with an unknown object or process being analysed [13]. Thus, the random search method was selected to be used for the parameter optimization of the process control system for waveguide path induction soldering.

The random search method has several different variations:

1) the size and step at each iteration method can be a constant or chosen individual for each iteration;

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2) the possibility to return after a bad step can be present or absent;

3) the choice of coordinates whose value should be changed on iteration can be made randomly or on the basis of additional obtained information.

The following random search method modification was selected in this study:

1) a different step value is selected by the researcher for each iteration, due to the active direct participation of researchers in the process of parameter optimization;

2) return after a bad step;

3) the search direction is chosen at random due to limited information about the process.

6. Experimental study

Using the random search method, a selection of the optimal values for the technological process initial parameters was made for the following waveguide sizes:

1) 58 × 25 mm;

2) 35 × 15 mm;

3) 19 × 9.5 mm.

The search for optimal parameters ends when the values of the target functions reached 5 degrees Celsius, due to technological regulations.

Table 2 provides step-by-step solution results for the optimization problem of searching for optimal parameters for a waveguide with a size of 58 × 25 mm. The solution is marked in bold. Figure 4 illustrates the search process in the coordinate space of the optimized parameters.

Table 2. Step-by-step solution results for the optimization problem for size 58 × 25 mm

Iteration of the algorithm	Power (W), kW	The size of the gap (h), mm	The action of the algorithm	The value of the objective function, degrees Celsius
1	5	5	Beginning	30.7
2	5	6	Transition	24.3
3	7	6	Transition	21.1
4	9	6	Transition	16.4
5	9	5.5	Transition	10.7
6	**10**	**5.5**	**End of the search**	**2.5**

Table 3 provides step-by-step solution results for the optimization problem of searching for optimal parameters for a waveguide with a size of 35 × 15 mm. The solution is marked in bold. Figure 5 illustrates the search process in the coordinate space of the optimized parameters.

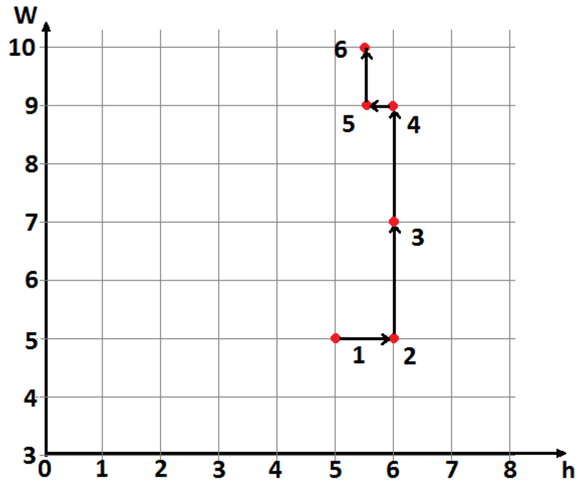

Figure 4. The search process for the optimal parameters for a standard size 58 × 25 mm

Table 3. Step-by-step solution results of optimization problem for size 35 × 15 mm

Iteration of the algorithm	Power (W), kW	The size of the gap (h), mm	The action of the algorithm	The value of the objective function, degrees Celsius
1	5	3	Beginning	21.5
2	6	3	Transition	17.6
3	7	3	Transition	9.7
4	8	3	Return	15.1
5	**7**	**4**	**End of the search**	**4.1**

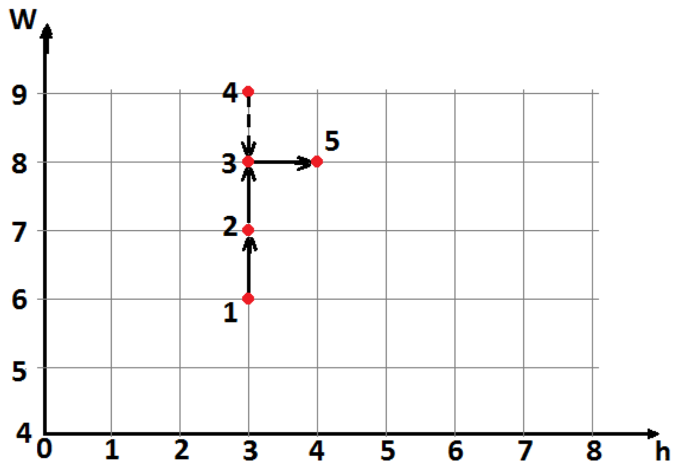

Figure 5. The search process for the optimal parameters for a standard size 35 × 15 mm

Table 4 provides step-by-step solution results for the optimization problem of searching for optimal parameters for a waveguide with a size of 19 × 9.5 mm. The solution is marked in bold. Figure 6 illustrates the search process in the coordinate space of the optimized parameters.

Table 4. Step-by-step solution results of optimization problem for size 19 × 9.5 mm

Iteration of the algorithm	Power (W), kW	The size of the gap (h), mm	The action of the algorithm	The value of the objective function, degrees Celsius
1	3	5	Beginning	42.4
2	3	4	Transition	23.7
3	3	3	Transition	17.1
4	3	2	Return	27.8
5	4	3	Transition	14.3
6	5	3	Transition	10.3
7	6	3	Return	18.7
8	**5**	**2.5**	**End of the search**	**3.8**

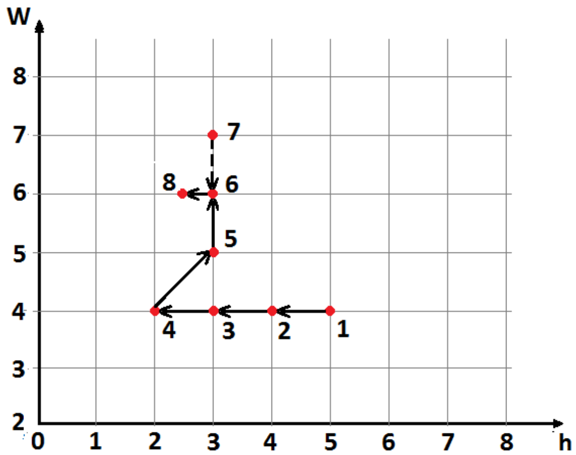

Figure 6. The search process for the optimal parameters for a standard size 19 × 9.5 mm

In Table 5 are shown the best initial values of the soldering process control parameter for different types and sizes of waveguides.

Table 5. - Optimal initial values of the soldering process control parameter

Size, mm	Power (W), kW	The size of the gap (h), mm
58x25	10	5.5
35x15	7	4
19x9.5	5	2.5

7. Discussion of results

From the data in Tables 2, 3 and 4 it is obvious that the application of the random search method allows the initial parameters for the control process of waveguide path induction soldering to be optimized under the conditions of a limited series of full-scale experiments.

The optimization of the explored waveguide size parameters did not demand more than eight iterations of the algorithm, which confirms the effectiveness of the target function selection (2) and random search method implementation to solve the stated problem.

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The method allowed us to optimize settings for a wide range of types and sizes of waveguide paths, thus confirming the possibility of its application to the stated problem.

8. Conclusion

The following results were achieved in the study:

1) a form of target function for optimizing the initial parameters for the technological process of the induction soldering of aluminium alloy waveguide paths was proposed, and an effective method for parameter optimization was selected;

2) the best technological process initial parameters for the induction soldering were received for the standard sizes of 58x25 mm, 35x15 mm and 19x9.5 mm;

3) the effectiveness of using the random search method was confirmed, a method which can be used in the future to optimize control parameters for sizes that have not been investigated in the study.

The proposed decision allows the technological parameters to be optimized for the induction brazing process, reducing time, material and labour costs associated with the need to conduct full-scale experiments.

Thus, the practical significance of the research is confirmed.

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