

A control algorithm for waveguide path induction soldering with product positioning¹

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Abstract. In the article, the problem of developing a control algorithm is described for the induction soldering process of aluminium alloy waveguide paths. The authors suggest a solution using logic controllers in two loops: controlling the speed at which product elements heat up and controlling the waveguide assembly movement relative to the plane of the inductor. The proposed solutions are based on the analysis of the thermal processes occurring in the waveguide pipe and the flange/coupler. Based on the results of numerical experiments, forms of control actions in the system and their parameters were selected. The proposed approach to generating such a control was tested in a series of waveguide path soldering field experiments and the obtained graphs showing the heating of product elements allow the efficiency of the developed logic controllers to be confirmed. The application of the proposed approach provides the high quality regulation of the induction heating process and also the possibility to obtain reliable permanent connections between elements of waveguide paths. Through the flexible adjustment of the proposed logic controller parameters, the high versatility of their use can be demonstrated.

1. Introduction

The technological processes of induction soldering are of key importance in a number of industries. Perfection of these processes is vital in ensuring a high quality product and in improving productivity [1,2].

The theory and practice of induction heating, the calculation and design of induction plants, and the development of automatic control systems are the subjects of many works of such scientists as A. V. Sluhocki, S. E. Ryskin, V. S. Nemkov, V. D. Laptinok, A. V. Murygin S. V. Shapiro, A. S. Vasiliev, P. N. Silchenko, M. Mihnev, V. B. Demidovich, A. A. Shulyak and L. E. Roginskaya, as well as a number of Russian and foreign enterprises, such as VNIITVCH-ESTEL (G. S.-Petersburg), NKTB "Vihr", NPP "Kuraj", NPO "Parallel" (Ufa), IJST "EKOM", (Krasnoyarsk), ABB, INDUCTOHEAT (USA). However, there are a number of topical issues requiring further research.

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2. Features of induction soldering

The assembly process by means of the induction soldering of lightweight elements made of aluminium alloys is complicated by the presence of a number of external factors, the greatest difficulty in which relates to a low degree of repeatability in the non-automated, manual soldering process. These factors also concern a high level of complexity in the visual control of the heating of elements, sometimes even rendering this impossible, the distortion of the electromagnetic field of the inductor, through its interaction with various conducting bodies in close proximity to the soldering area, and the negative impact of the human factor, among others. [3,4]. The cumulative impact of these and other factors leads to uncorrectable defects in the manufacture of waveguide soldered joints. The number of defects that are unable to be corrected is of up to 5 %.

At the same time, the complex automation of the technological processes of induction soldering that should allow the influence of the above factors to be neutralized is in turn also constrained by several factors, including the insufficient study of electrothermal processes in the assembly of the induction soldering of waveguide paths, poor precision and limited capabilities of the automated control systems of induction heating processes, as well as the lack of reliable feedback systems between the automated control system unit, technological equipment and soldering area [5,6].

Since the commissioning of assembly technology for the induction soldering of waveguide paths elements, significant experience has been gained of various control systems for the automation of soldering processes (including systems using machine vision and control systems of power parameters, among others). At the same time, there are limited solutions to the challenges posed by the issues of ensuring the required accuracy of the automated control systems for soldering process, and the required characteristics of the equipment and tooling.

The technological process involved in the assembly for the induction soldering of waveguide paths can be represented as a system of interacting elements (technological operations, their cycles, methods and equipment and management systems), considered as a whole. Together, these issues have engaged scientists Faure, A., Sidorov V. I., Kuropatkin P. V., Stepanov M. F., Gladkov E. A., Reznik A. L. and others.

Since the commissioning of assembly technology for this process, significant experience has been acquired with various technological equipment, means and methods of measuring process parameters, and the process control system for automation of soldering process [7,8].

3. Automation of the induction soldering process

Methodologically, the development of automated technological systems requires a systematic approach. It involves the definition of basic input and output process parameters, the selection of control actions and the development of sensors for the main technological parameters, the identification of the control object (the construction of mathematical models of the process), and the definition of optimal modes and synthesis of the control system.

When control of the technological processes is in conjunction with mathematical models, there is a necessity to use other modern methods of identifying control objects and adaptive control system theory with feedback on key process parameters.

Authors made the decision to use contactless pyrometric sensors in developing the complex automated equipment. The main requirements for the choice was higher temperature control precision (less than 0.5%), the diameter of the controlled spot not being more than 1.5 mm. (to allow temperature control in the gap of the inductor-waveguide), electromagnetic interference immunity and its connection to a computer [9,10].

AST 250 pyrometers were selected as non-contact temperature sensors as they best satisfy the above requirements.

In the study of thermal fields during the waveguide element induction heating, it was determined that for the automation of the process of waveguide path element induction soldering 2 pyrometers are sufficient: one for temperature control on the waveguide flange and the other on the waveguide tube.

The results of experimental studies of the induction soldering process of various sizes waveguide paths revealed the following pattern: software power control of the heating allows the reproduction of the temporal temperature characteristic only for one element of the connection waveguide tube. The temperature of the second element, the flange (coupling area), may significantly differ from the temperature of the pipe by $30\div 70$ degrees Celsius. With the right choice of starting distance from the flange to the inductor, it is possible to reduce the temperature difference in the vicinity of the melting solder temperature. However, it is not possible to completely eliminate the range of temperatures because of the scatter of the waveguide tube thickness, which can be over 20% of the nominal thickness. This problem can be solved by the automatic adjustment of the distance from the flange to the inductor during the technological process of soldering. The structure of the control system is double-circuit linked.

In connection with this, a new dual-circuit functional diagram for the automated process control system of induction soldering was developed (Fig. 1), by changing the power supplied to the inductor and the distance from the inductor to the heated product. Such a control scheme allows the heating of waveguide path elements to be performed according to a given law, ensuring the desired temperature distribution on the heated object.

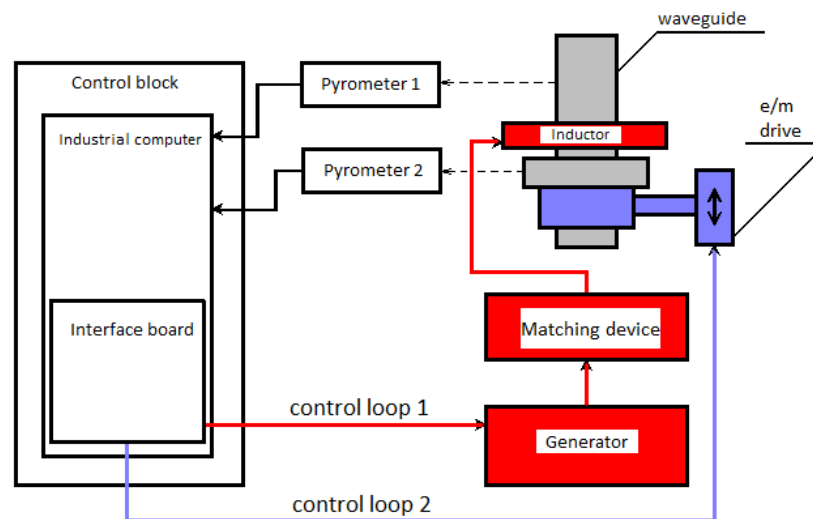


Figure 1. The structural scheme of automated equipment

Circuit 1 provides the control of power supplied to an inductor. Circuit 2 enables control of the electromechanical manipulator drive and allows the position of the soldered waveguide elements to be changed relative to the inductor.

Control of the process technological parameters is performed by the computer using error signals obtained as a result of the comparison of the program temperature with pyrometers controlling the temperature of the waveguide tube and flange [11,12].

4. Approaches to regulation in the control system of the soldering technological process

The double-loop process control system for the induction soldering of aluminium alloy waveguide paths in terms of automatic control systems can be represented by a diagram as follows (Fig. 2):

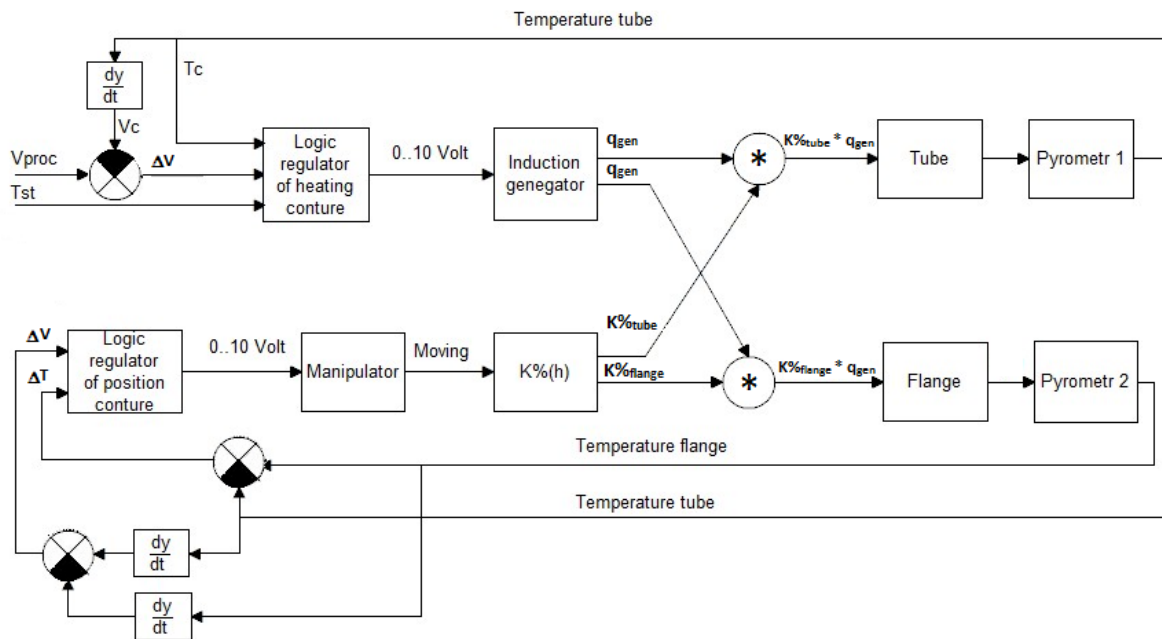


Figure 2. General scheme of the induction soldering system control

In the figure the following notation is used:

- V_{proc} is setpoint speed of heating;
- T_{st} is temperature stabilization;
- q_{gen} is generator power transferred to the brazed product;
- $K\%$, (h) is the distribution of energy between the generator elements of the product as a percentage.

For the most trivial tasks, maintaining a given heating mode is suitable for the parametric integral differential (PID) controller. However, in this task, one of the control circuits (the distance between the inductor and the device) is indirect and the use of PID control on all stages of the process is ineffective. For example, the introduction of the control loop integral component of the drive leads to a deterioration in the quality of control. It is connected to the relatively high inertia of the control object, which has already resulted in an integral link in the in the control loop, and it is not possible to improve this procedure.

Modern research considers the types and combinations of parametric (P) and differential (D) controllers, which would allow the heating rate and the temperature difference among product elements to be controlled independently of the control loop: the P-controller allows the temperature difference to be controlled, and the D-controller allows the heating rate of each of the elements to be managed.

Due to the introduction of the control loop of the workpiece position relative to the window of the inductor, the control system acquires the properties of being multi-connected and nonlinear. The mutual influence of loops can be weakened through the pulse control

system (1) so each of the circuits independently of each other are subjected to the law with constant intervals of control and waiting:

$$imp(t, \tau_1, \tau_2) = \begin{cases} 1, & \text{if } mod\left(\frac{t}{\tau_1 + \tau_2}\right) \leq \tau_1, \\ 0, & \text{otherwise,} \end{cases} \quad (1)$$

where τ_1 is the control interval; τ_2 is the waiting interval; $mod(x_1/x_2)$ is the calculation of the remainder from dividing x_1 by x_2 ; t is time.

Such an approach means that it is not necessary to calculate precise measures of mutual influence of loops and improves the quality of control for the following reasons:

- it eliminates the problem of high inertia of the control object relative to the control device;
- it decreases the mutual influence of the loops.

In this case, the choice of sufficiently small intervals of control and waiting (200 – 400 ms) allows renders the mutual influence of control loops negligible relative to the control.

5. The heating speed control loop

When regulating the heating speed, control is based on the logical integral controller for the deviation of the heating temperature for the soldered elements of the product above a certain threshold. In addition, separate modes of operation can be selected depending on the stage of the process:

- warm-up;
- main heating;
- stabilization phase.

As a result of exploratory research, for the first control loop (temperature control), the control dependence could be represented as a logical function (2):

$$u_1(t) = Wint(t) + imp(t, \tau_1, \tau_2) * \begin{cases} 0 & \text{if } T_c(t) < T_{sns}, \\ \frac{|\Delta V(t)|}{\Delta V(t)} * k_1, & \text{if } T_c(t) < T_{st} \text{ and } |\Delta V(t)| > V_{sns} \text{ and } T_c(t) > T_{sns}, \\ \frac{|\Delta V(t)|}{\Delta V(t)} * k_2, & \text{if } T_c(t) > T_{st} \text{ and } |\Delta V(t)| > V_{sns} T_c(t) > T_{sns}, \\ -k_3, & \text{if } T_c(t) > T_{st} + T_{lim}. \end{cases} \quad (2)$$

where T_{sns} is the sensitivity temperature of the measuring device (pyrometer); $\Delta V(t)$ is the difference in the rates of increase between the controlled temperature (on one of the elements of the soldered assembly) and the heating rate program. It is calculated by the formula:

$$\Delta V(t) = V_{proc}(t) - V_c(t)$$

$V_{proc}(t)$ is the heating rate program; $V_c(t)$ is the heating rate of the soldered assemble element; V_{sns} is the tolerance threshold of the controlled heating rate; $T_c(t)$ is the temperature of the soldered assemble element (on which is the control loop); T_{st} is the stabilization mode temperature; T_{lim} is the permissible limit of exceeding the stabilization temperature; k_1 is the change constant of the control signal at the stage of preheating to the stabilization temperature; k_2 is the change constant of the control signal at the temperature stabilization phase; k_3 is the change constant of the control signal when exceeding the permissible heating

limit at the stage of stabilization of the temperature; W_{int} is the integral component of the transfer function:

$$W_{int} = \frac{1}{a * s}, a \rightarrow 0.$$

6. The control loop of the workpiece position relative to the plane of the inductor

The control formation in the second control system loop is much more complex compared to the first control loop.

The control of the process of waveguide induction soldering can be divided into separate stages, each of which can be in various conditions. On the basis of system state analysis, it is possible to allocate the desired control law at a certain stage to the system state. Since the system is non-stationary, multivariable and nonlinear, the control problem cannot be solved in a trivial way using a standard control law, and requires a structural solution that covers all of the many possible states.

Table 1 presents the correlation of the technological process stages, the control object state and the ideas of control.

Table 1. Correspondence between technological process stages, states of the control object and the idea of control

Stage of the technological process	State of the control object	The idea of control
Preheating the workpiece to 300 degrees Celsius and levelling the temperature of the product elements.	Initial temperature spread of the soldered elements.	As soon as possible, eliminate the amount of misalignment.
Heating the workpiece to the soldering temperature	The transient or steady-state value in a system in which the temperatures of the elements are equal and have the same rate of increase	Ensure the convergence of the temperature of the elements and the equalization of the rates of their growth. Keeping the heating rate and the temperature difference within acceptable limits.
Melting of solder with formation of soldered joint.	A nonlinear process accompanied by a change in the temperature fields due to heat exchange between the elements	Maintaining the temperature at a given level - the melting point of the solder. Avoid overheating of the main material.

For every control idea presented in Table 1 is suitable a particular control law, which is implemented in a separate logic controller with defined coefficients. This statement is supported by the results of the mathematical modelling of the system, by searching for the main regulators using different gain values (Figures 3 and 4).

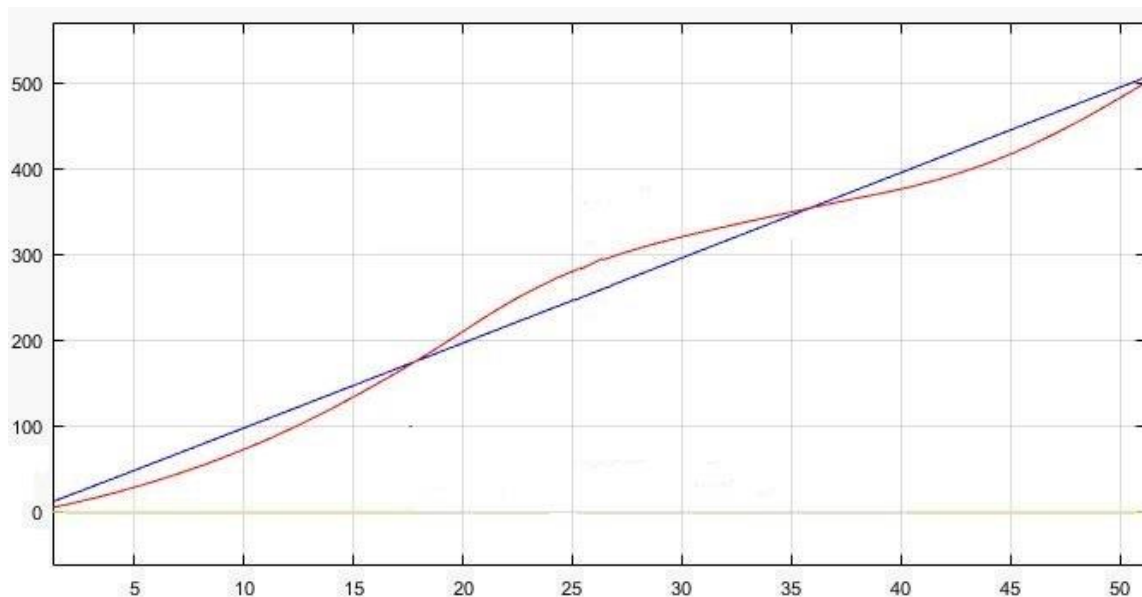


Figure 3. Simulation of the system with the P-controller.

Red graph - The temperature of the pipe, Blue graph - The temperature of the flange.
Y axis – temperature, X axis – time.

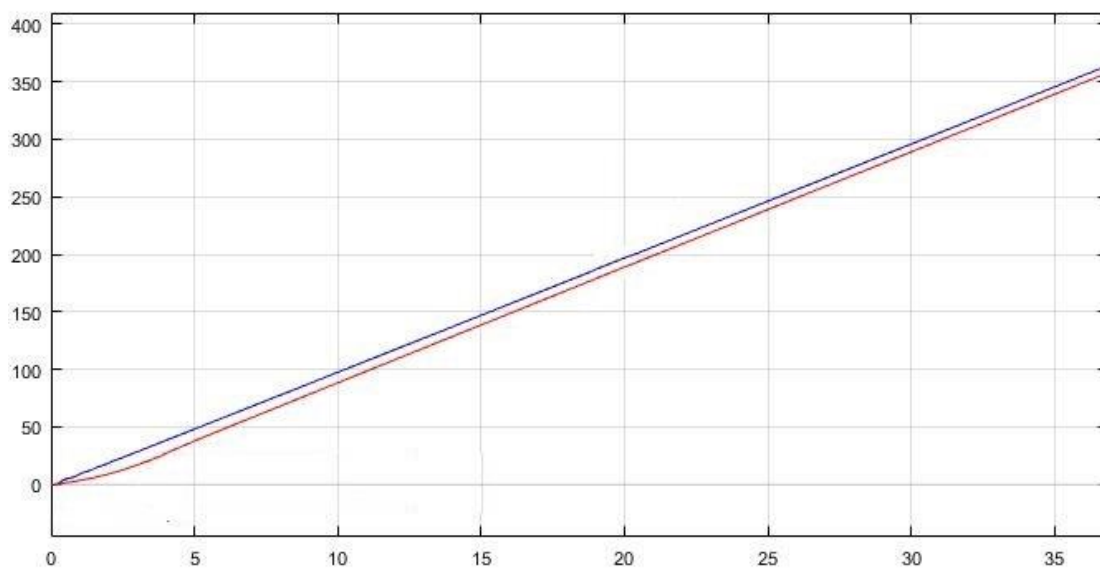


Figure 4. Simulation of the system with the D-controller.

Red graph - The temperature of the pipe, Blue graph - The temperature of the flange.
Y axis – temperature, X axis – time.

As can be seen in Figure 3, the P-controller allows graphs of the heating element temperatures to be plotted closer to each other. However, the system is in an oscillatory state, and the magnitude of the error signal is constantly changing. This P-controller with a small gain allows small deviations of the system from a given regime to be corrected.

From Figure 4 it can be seen that the D-regulator allows the rate of heating to be equalized, but the magnitude of the temperature difference between the soldered elements remains constant.

As can be deduced from the above, the development of the control law on the basis of different combinations of P- and D-controllers can fully satisfy the needs for quality control. Table 2 presents the relationship between the ideas identified for control and their implementation in the form of certain types of regulators.

Table 2. Relationship of control ideas and regulators

The idea of control	Regulator
As soon as possible, eliminate the temperature mismatch	P-regulator (with high gain).
Ensuring the convergence of temperatures and their equalization of velocities.	D-regulator. PD controller.
The retention of the heating rate and the temperature difference.	P-controller (low gain). PD - regulator.
Maintaining the temperature at the melting point of the solder	
Preventing overheating of the main material	

According to the results of experimental studies, the dependence for control for the second control circuit has been found and can be represented by a logical function (3):

$$u_2(t) = \text{imp}(t, \tau_1, \tau_2) * \begin{cases} \frac{|\Delta T(t)| * k_1}{k_{\text{simple}}}, & \text{if } |\Delta T(t)| > \Delta T_{\text{max}} \text{ and } T_{tb}(t) > T_{sns} \text{ and } T_{fl}(t) > T_{sns}, \\ \frac{(T_{fl}(t) - T_{sns}) * k_1}{k_{\text{simple}}}, & \text{if } T_{fl}(t) > T_{sns} \text{ and } T_{tb}(t) < T_{sns}, \\ \frac{(T_{tb}(t) - T_{sns}) * k_1}{k_{\text{simple}}}, & \text{if } T_{tb}(t) > T_{sns} \text{ and } T_{fl}(t) < T_{sns}, \\ \frac{|\Delta V(t)| * k_2}{k_{\text{simple}}}, & \text{if } |\Delta T(t)| < \Delta T_{\text{max}} \text{ and } |\Delta V(t)| > \Delta V_{\text{max}}, \\ \frac{|\Delta V(t)| * k_2 - |\Delta T(t)| * k_3}{k_{\text{simple}}}, & \text{if } |\Delta T(t)| < \Delta T_{\text{max}} \text{ and } \Delta V_{\text{min}} < |\Delta V(t)| < \Delta V_{\text{max}}, \\ \frac{|\Delta T(t)| * k_4}{k_{\text{simple}}}, & \text{if } |\Delta T(t)| < \Delta T_{\text{max}} \text{ and } |\Delta V(t)| < \Delta V_{\text{min}}. \end{cases} \quad (3)$$

where T_{sns} is the sensitivity temperature of the measuring device (pyrometer); $\Delta V(t)$ is the difference in the rate of increase in temperature of elements. It is calculated as:

$$\Delta V(t) = V_{fl}(t) - V_{tb}(t);$$

$\Delta T(t)$ is the temperature difference between the assembled elements. It is calculated as:

$$\Delta T(t) = T_{fl}(t) - T_{tb}(t);$$

$T_{fl}(t)$ is the current flange temperature; $T_{tb}(t)$ is the current waveguide temperature; $V_{fl}(t)$ is the current flange heating rate; $V_{tb}(t)$ is the current tube heating rate; ΔV_{max} is the upper threshold of regulator activation; ΔV_{min} is the lower threshold of regulator activation; ΔT_{max} is the threshold for regulating the temperature of the process; k_1, k_2, k_3, k_4 are the gain factors of individual regulators; k_{simple} is the common coefficient of reduction to one order.

The above mathematical models for the regulation have already been implemented within an automated control system.

7. Experimental studies

Authors used 3 sizes of waveguide tubes and flanges/couplings when conducting experimental studies for testing the proposed approach to the control of the induction soldering of aluminium alloy waveguide paths:

- 1) 58×25 mm;
- 2) 35×15 mm;
- 3) 19×9.5 mm.

Figures 5, 6, 7 show the graphs of the soldering process. In each case, high-quality solder joints were obtained.

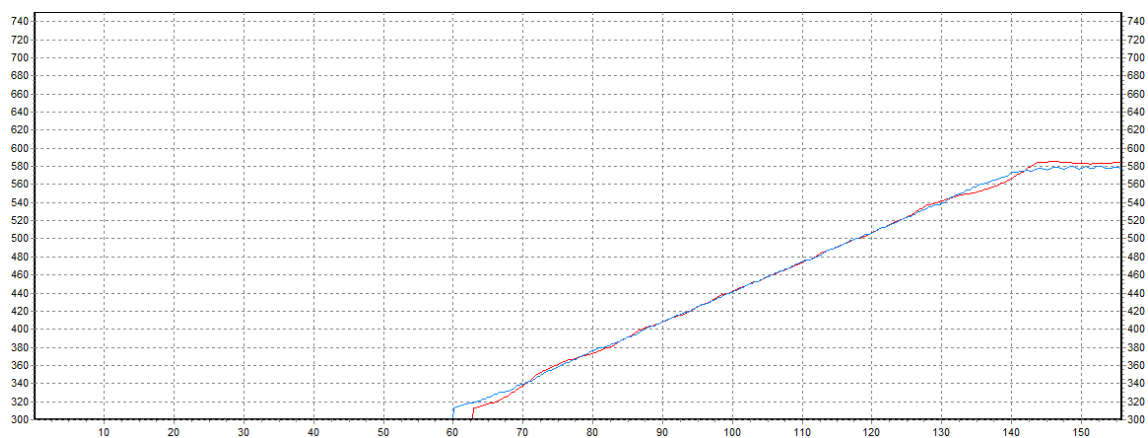


Figure 5. Soldering process for the standard size 58×25 mm

Red graph - The temperature of the pipe, Blue graph - The temperature of the flange.

Y axis – temperature, X axis – time.

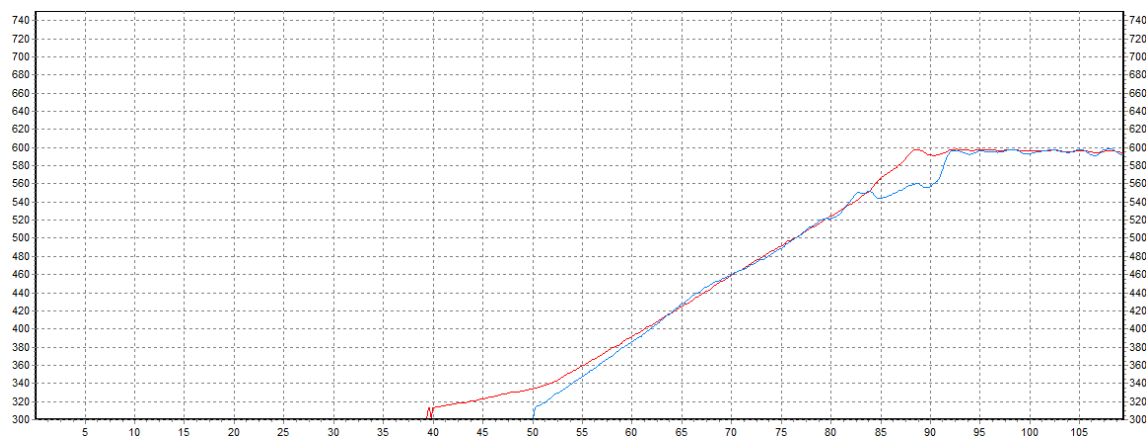


Figure 6. Soldering process for the standard size 35x15 mm

Red graph - The temperature of the pipe, Blue graph - The temperature of the flange.

Y axis – temperature, X axis – time.

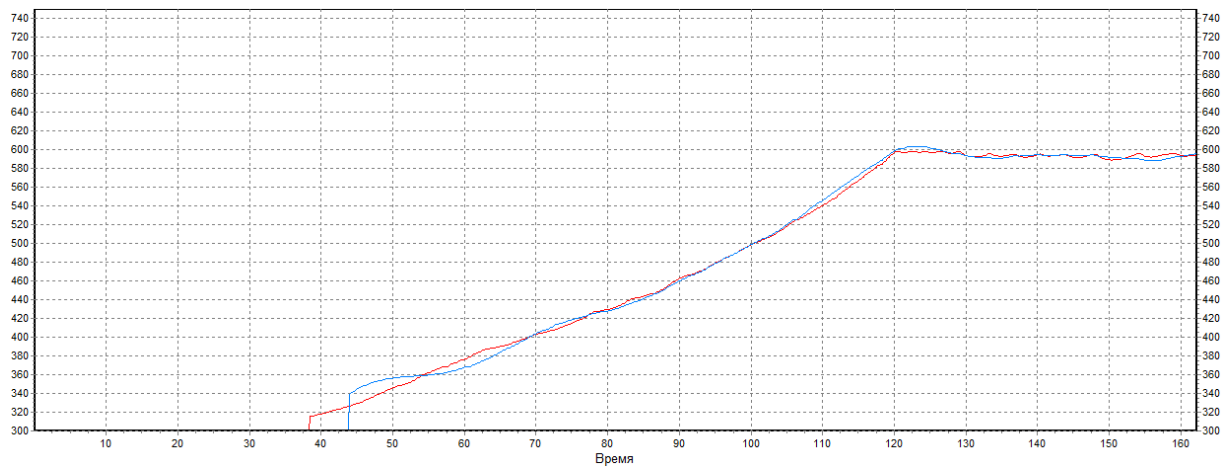


Figure 7. Soldering process for the standard size 19x9.5 mm

Red graph - The temperature of the pipe, Blue graph - The temperature of the flange.

Y axis – temperature, X axis – time.

8. Discussion of results

The graphs in Figures 5, 6 and 7 show that the differences in the sizes of soldered products do not have a significant impact on the quality of control. The proposed logic controllers (2, 3) for the induction soldering technological process can be used without reconfiguration of their settings for each individual size.

At each stage of soldering the idea of control (Tab. 1) was successfully realized, which confirms the correctness of the choice of control laws and the conditions of their application.

In Figure 5, the temperature of the product elements was recorded with a small-time difference and have a small initial misalignment, so there is almost no overshoot before melting the solder. Furthermore, upon reaching the melting temperature, the process of stabilizing the product element temperatures occurs with the subsequent formation of high quality solder joints.

In Figure 6, initial overheating of the waveguide pipe is visible, wherein the system reaches a steady state before melting the solder, after which the temperature graphs reconverge and the solder joints are formed. In addition, it is clear that the resulting non-linear process of redistribution of the product element temperature fields can be regulated by the end of the melting of the solder and the joint being completed.

In Figure, 7, as a result of the initial distribution of temperatures occurs a quickly fading oscillatory process, after which the system in a steady state brings the technological process to the stage of the solder melting and its successful completion.

In all these cases, high-quality solder joints were achieved. In addition, all of the graphs showing the processes of induction soldering (Fig. 5, 6 and 7) show that the choice of pulse character for controlling the automated system reduces the impact of the cross-coupling of loops to an insignificant level and improves the quality of control.

9. Conclusion

The following results were obtained in the current study:

1) the form and the types of regulators that allow the induction soldering process for aluminium alloy waveguide paths to be controlled without any need to reconfigure their internal state, which indicates the versatility of their use for a wide range of waveguide sizes;

2) the application of impulse control in the system allowed the cross-influence in the system to be reduced to a negligible level, thereby providing an appropriate regulatory process;

3) using the developed control system allows a high-quality soldering connection to be obtained for aluminium alloy waveguide paths.

Thus, the study addresses the problem of generating effective control for the double-circuit system for the induction soldering of aluminium alloy waveguide paths, which assures the high quality of soldered joints and reduces the human impact on the technological process.

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