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SIMULATION OF THE INDUCTION SOLDERING PROCESS OF WAVEGUIDE PATHS FROM ALUMINUM ALLOYS

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A system of waveguide paths is a complex structure of various elements with various geometries. Induction soldering based on the induction heating method is one of the promising methods for waveguides fabricating. Induction soldering of waveguide paths has a number of technological features: the melting temperature of the base material AD31 (695–663 ^{0}C) slightly differs from the melting temperature of St. AK12 solder (577–580 ^{0}C) at an average induction heating rate of 20–25 ^{0}C / sec; a wide variety of standard sizes of waveguide paths elements complicates the development and subsequent reproduction of technological parameters of the induction soldering process; zones of maximum heating of waveguide paths elements do not coincide with zones of soldering. Therefore, to solve the problems of controlling the waveguides soldering process, it is necessary to simulate this process. The paper deals with the problem of simulating the process of heating a waveguide during induction soldering. Requirements for the process model have been formed. The model is built on the basis of the differential heat conduction equation. The formed model requirements take into account the geometric parameters of waveguides, the physical parameters of materials, the initial and boundary conditions, as well as the uneven distribution of eddy current density in the waveguide. It is proposed to use the finite difference method for the numerical solution of the heat conduction equation. The process of calculating the temperature at the grid nodes is shown. The authors propose a two-stage solution. At the first stage, at an intermediate time step, the temperature at the grid nodes along the X axis is calculated. At the second stage, the temperature at the grid nodes along the Y axis is calculated. The numerical solution of the difference equations along the X and Y axes is carried out by the sweep method. An algorithm for the numerical solution of the heat conduction equation has been developed.

Keywords: waveguide path, induction soldering, model of the waveguide heating process, differential heat conduction equation, finite difference method.

МОДЕЛИРОВАНИЕ ПРОЦЕССА ИНДУКЦИОННОЙ ПАЙКИ ВОЛНОВОДНЫХ ТРАКТОВ ИЗ АЛЮМИНИЕВЫХ СПЛАВОВ

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Система волноводных трактов представляет собой сложную конструкцию из различных элементов с разнообразной геометрией. Одним из перспективных способов изготовления волноводов является индукционная пайка, основанная на методе индукционного нагрева. Индукционная пайка волноводных трактов обладает рядом технологических особенностей: относительно небольшая разница температуры плавления основного материла АД31 (695–663 ^{0}С) и припоя Св. АК12 (577–580 ^{0}С) при средней скорости индукционного нагрева 20–25 ^{0}С/сек; большое разнообразие типоразмеров элементов волноводных трактов представляет сложность при отработке и последующем воспроизведении технологических параметров процесса индукционной пайки; зоны максимального нагрева элементов волноводных трактов не совпадают с зонами пайки. Поэтому для решения задач управления процессом пайки волноводов необходимо провести моделирование данного процесса.

В статье рассмотрена задача моделирования процесса нагрева волновода при индукционной пайке. Сформированы требования к модели. Модель строится на основе дифференциального уравнения теплопроводности. Сформированные требования к модели учитывают геометрические параметры волноводов, физические параметры материалов, начальные и граничные условия, а также неравномерное распределение плотности вихревого тока в волноводе. Предлагается для численного решения уравнения теплопроводности использовать метод конечных разностей. Показан процесс расчета температуры в узлах сетки. Решение осуществляется в два этапа. На первом этапе на промежуточном временном шаге проводится расчет температуры в узлах сетки по оси X, на втором этапе вычисляется температура в узлах сетки по оси Y. Численное решение разностных уравнений по оси X и Y осуществляется методом прогонки. Разработан алгоритм численного решения уравнения теплопроводности.

Ключевые слова: волноводный тракт, индукционная пайка, модель процесса нагрева волновода, дифференциальное уравнение теплопроводности, метод конечных разностей.

Introduction. Systems of waveguide paths are widely used in spacecraft to ensure their functioning and transmission of electromagnetic energy in them [1].

A system of waveguide paths is a complex structure of various elements with various geometries (fig. 1).

Various methods are used to connect the structural elements of waveguide paths: argon-arc welding, soldering in salt baths, soldering using a laser source [2–5].

Induction soldering is one of the promising methods for waveguide paths fabricating [1; 3].

Induction soldering provides contactless, fast and local heating of the soldering point. It reduces the oxidation of current-carrying surfaces and waveguide warping. The equipment providing induction heating is rather compact and easily controlled, which allows automated controlling the soldering process [6].

However, induction soldering of waveguide paths has a number of features [7]:

1. The melting temperature of the base material AD31 (695–663 ^{0}C) slightly differs from the melting temperature of St. AK12 solder (577–580 ^{0}C) at an average induction heating rate of 20–25 ^{0}C / sec.

2. A wide variety of standard sizes of waveguide paths elements complicates the development and subsequent reproduction of technological parameters of the induction soldering process.

3. Zones of maximum heating of the waveguide paths elements do not coincide with zones of soldering.

Therefore, it is necessary to simulate the process of heating the waveguide before setting the problem of controlling the process of waveguide paths induction soldering.

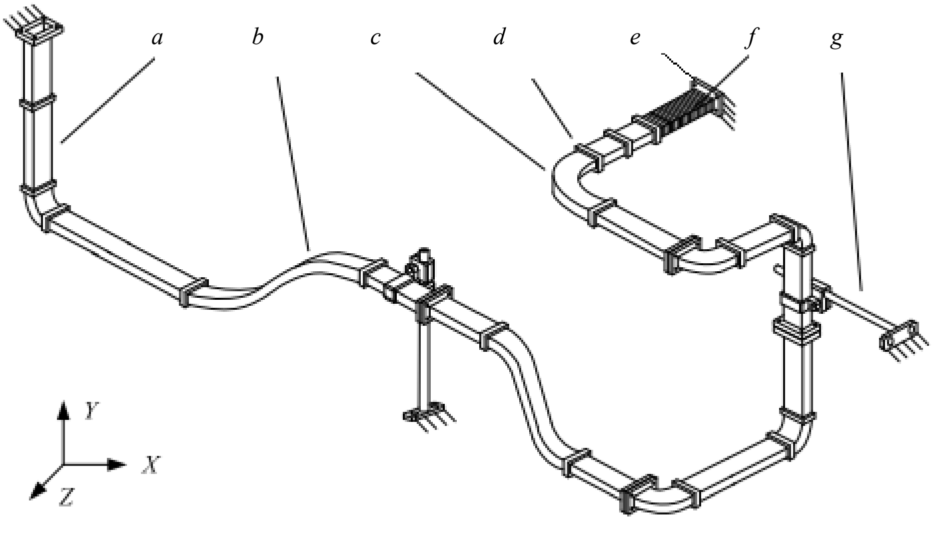
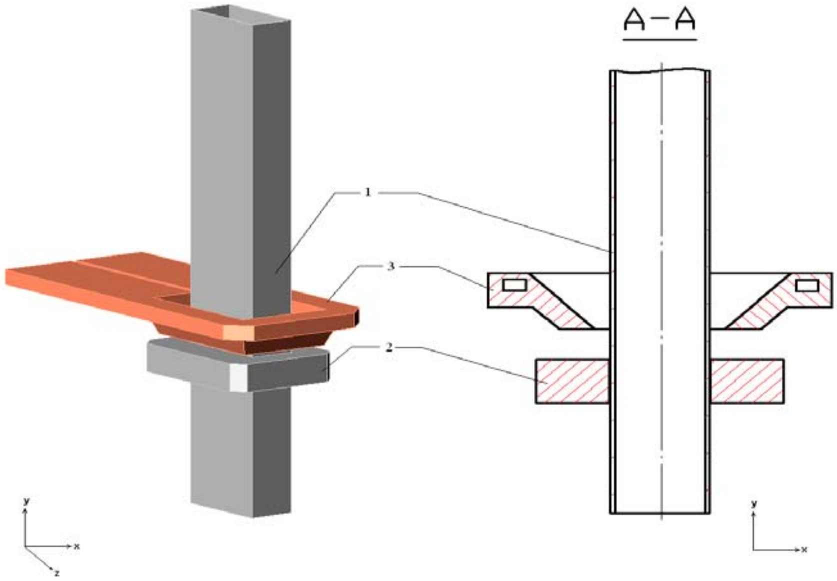


Fig. 1. An example of a section of a waveguide distribution system:
a – a direct element; *b* – a curved element with a variable radius of curvature;
c – a curved element with a constant radius of curvature; *d* – a coupling; *e* – a flange;
f – a flexible section; *g* – an intermediate support

Рис. 1. Пример участка волноводно-распределительной системы:
а – прямой элемент; *б* – криволинейный элемент с переменным радиусом кривизны;
в – криволинейный элемент с постоянным радиусом кривизны; *г* – соединительная муфта;
д – фланец; *е* – гибкая секция; *ж* – промежуточная опора



а *б*

Fig. 2. The researched system "inductor – waveguide":
1 – a waveguide pipe; *2* – a flange; *3* – an inductor

Рис. 2. Исследуемая система «индуктор – волновод»:
1 – волноводная труба; *2* – фланец; *3* – индуктор

Construction of a waveguide heating model. The connection of the straight section of the waveguide tube and the flange was chosen as a typical object for considering the process of induction heating (fig. 2).

The inductor (without considering the power part of the induction equipment) is a ring made of copper (fig. 2). The inductor is a source of alternating magnetic field, which forms eddy currents flowing in the waveguide. The calculation of a simplified two-dimensional waveguide-inductor circuit showed that the eddy currents in the waveguide are unevenly distributed [8–10].

Based on the above, it is possible to construct a mathematical model of heating the waveguide path during induction soldering, taking into account the following assumptions:

– the spatial configuration of the system allows us to restrict ourselves to a simplified two-dimensional model;

– a general model can be used to simulate a pipe-flange system, since the waveguide elements can be represented by plates in a simplified form.

For a generalized model of thermal processes occurring during induction soldering of waveguide paths, we take the differential equation of heat conduction [11]. Since the heating of the waveguide is due to eddy currents flowing in it, a permanent heat source is added to the formula:

$$\frac{\partial T(x,y,t)}{\partial t} = a\left(\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2}\right) + q(x,y,t), \quad (1)$$

where a is the coefficient of thermal diffusivity of the material; T is temperature; t is time; x, y are Cartesian coordinates; $q(x, y, t)$ is a permanent source of heat.

Equation (1) describes a variety of options for the waveguide heating process flow. Therefore, in order to simulate the thermal processes occurring during induction soldering, it is necessary to add single-valued conditions to equation (1). Single-valued conditions may contain geometric, physical, initial and boundary conditions. These conditions are as follows:

– a simplified geometric two-dimensional model of the waveguide is adopted, shown in fig. 3;

– eddy currents are supposed to flow over the surface of the waveguide [12];

– it is taken into account that the eddy current density is distributed unevenly due to the shape of the waveguide and the location of the inductor relative to the waveguide [12];

– thermophysical characteristics of the waveguide material are constant;

– the initial temperature of the waveguide is the same along its entire length:

$$T(x,y) = T_i = \text{const};$$

– heat exchange with the environment (Newton's boundary condition) is carried out by the inner and outer surface of the pipe:

$$a\frac{\partial T(x,y,t)}{\partial x} = b(T(x,y,t) - Ten),$$

where b is the heat exchange coefficient; Ten is the temperature of the environment; $0 \le x \le l_p$ (inner side); $0 \le x \le l_p - h_f$ (outer side);

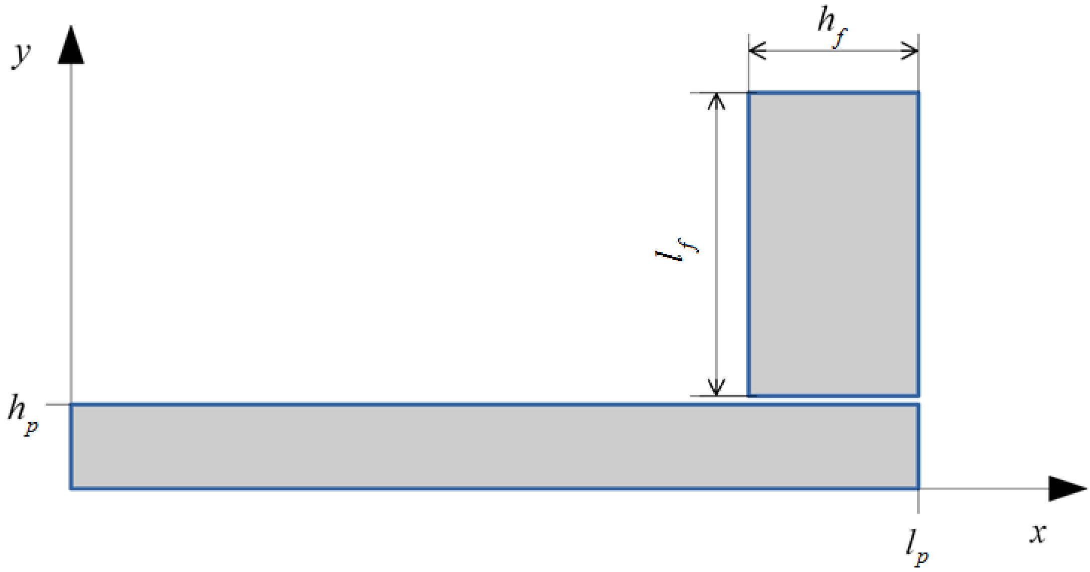


Fig. 3. A simplified geometric model of the waveguide:
l_p – length of a pipe; h_p – width of a pipe; h_f – width of a flange; l_f – length of a flange

Рис. 3. Упрощенная геометрическая модель волновода:
l_T – длина трубы; h_T – ширина трубы; h_f – ширина фланца; l_f – длина фланца

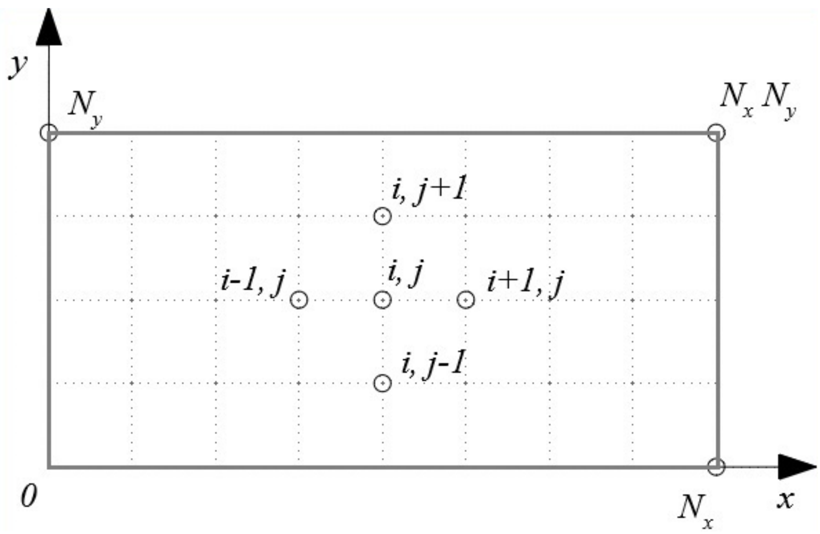


Fig. 4. A difference mesh of the solution domain

Рис. 4. Разностная сетка области решения

– heat exchange with the environment is carried out by the upper and side faces of the flange.

For the upper face:

$$a\frac{\partial T(x,y,t)}{\partial y} = b(T(x,y,t) - Ten),$$

where $h_p \le y \le h_p + l_f$.

For the side face:

$$a\frac{\partial T(x,y,t)}{\partial x} = b(T(x,y,t) - Ten),$$

where $l_p - h_f \le x \le l_p$;

– heating power remains constant $q(x,y,t) = \text{const}$;

– heat exchange between the pipe and the flange is assumed to be zero.

For the numerical solution of equation (1), we apply the finite difference method [13–15]. Let us consider the method applied to a waveguide tube.

To approximate equation (1) by the finite difference method, we represent the pipe as a set of nodes with coordinates (fig. 4): $x_i = i \cdot h_x$, $y_i = j \cdot h_y$, $t_k = k\tau$, where h_x, h_y is the step along the coordinate grid x, y; τ is the time step.

Let us sample equation (1) in two stages. At the first stage, at an intermediate time step τ / 2, we carry out sampling along the *X* axis; at the second stage, we carry out sampling along the Y axis. We obtain equation (1) in the difference form [15]:

$$\frac{T_{ij}^{k+\frac{1}{2}} - T_{ij}^{k}}{\frac{t}{2}} = a\left(\frac{T_{i+1,j}^{k+\frac{1}{2}} - 2T_{ij}^{k+\frac{1}{2}} + T_{i-1,j}^{k+\frac{1}{2}}}{h_x^2}\right) + q_{ij}^{k+\frac{1}{2}}, \quad (2)$$

$$\frac{T_{i,j}^{k+1} - T_{i,j}^{k+\frac{1}{2}}}{\frac{t}{2}} = a\left(\frac{T_{i,j+1}^{k+1} - 2T_{i,j}^{k+1} + T_{i,j-1}^{k+1}}{h_x^2}\right) + q_{i,j}^{k+1}, \quad (3)$$

where $T_{ij}^{k} = T(x_i, y_j, t_k)$; $q_{i,j}^{k} = q(x_i, y_j, t_k)$.

Solving first equation (2), and then equation (3), we determine the temperature field at a whole time step.

Approximation of the boundary conditions for a pipe is as follows:

$$a\frac{T_{i,j+1}^{k} - T_{i,j}^{k}}{h_y} = b(T_{i,j}^{k} - Ten), \text{ if } 0 \le i \le N_x, j = 0,$$

$$a\frac{T_{i,j-1}^{k} - T_{i,j}^{k}}{h_y} = b(T_{i,j}^{k} - Ten), \text{ if } 0 \le i \le N_x, j = N_y.$$

The sweep method [14] is suitable for solving difference equations (2) and (3). Let us consider this method using the example of solving equation (2). We transform the equation (2) [14]:

$$\frac{T_{i,j}^{k+\frac{1}{2}}}{\frac{\tau}{2}} + a^2\left(\frac{T_{i,j}^{k+\frac{1}{2}}}{h_x^2}\right) = a\frac{T_{i+1,j}^{k+\frac{1}{2}}}{h_x^2} + a\frac{T_{i-1,j}^{k+\frac{1}{2}}}{h_x^2} + \frac{T_{i,j}^{k}}{\frac{\tau}{2}} + q_{i,j}^{k+\frac{1}{2}}.$$

Then

$$\left(\frac{1}{\frac{\tau}{2}} + \frac{2q}{h_x^2}\right)T_{i,j}^{k+\frac{1}{2}} = \frac{a}{h_x^2}T_{i+1,j}^{k+\frac{1}{2}} + \frac{a}{h_x^2}T_{i-1,j}^{k+\frac{1}{2}} + \frac{1}{\frac{\tau}{2}}T_{i,j}^{k} + q_{i,j}^{k+\frac{1}{2}}.$$

Hence we get

$$a_i T_{i,j}^{k+\frac{1}{2}} = b_i T_{i+1,j}^{k+\frac{1}{2}} + c_i T_{i-1,j}^{k+\frac{1}{2}} + d_i + q_{i,j}^{k+\frac{1}{2}}, \quad (4)$$

where

$$a_i = \frac{1}{\frac{\tau}{2}} + \frac{2q}{h_x^2};\ b_i = c_i = \frac{q}{h_x^2};\ d_i = \frac{1}{\frac{\tau}{2}}T_{i,j}^{k}.$$

For the boundary points 0 and N_x, we write equation (4) in the following form:

$$a_0 T_{0,j}^{k+\frac{1}{2}} = b_0 T_{i,j}^{k+\frac{1}{2}} + d_0, \quad (5)$$

$$a_N T_{N,j}^{k+\frac{1}{2}} = c_N T_{N-1,j}^{k+\frac{1}{2}} + d_N. \quad (6)$$

The sweep algorithm begins by writing equation (5) in the form:

$$T_{0,j}^{k+\frac{1}{2}} = P_0 T_{i,j}^{k+\frac{1}{2}} + Q_0 \quad , \quad (7)$$

where $P_0 = \frac{b_0}{a_0}$, $Q_0 = \frac{d_0}{a_0}$ are determined by the initial and boundary conditions of the simulation.

We substitute relation (7) into (4) for $i = 0$. Continuing the process of sequential substitution $T_{i,j}^{k+\frac{1}{2}}$ can be expressed through $T_{i+1,j}^{k+\frac{1}{2}}$:

$$T_{i,j}^{k+\frac{1}{2}} = P_i T_{i+1,j}^{k+\frac{1}{2}} + Q_i, \quad (8)$$

where P_i и Q_i are new coefficients obtained during the substitution process. Using expressions (8) and (4), we can obtain formulas for calculating P_i и Q_i:

$$P_i = \frac{b_i}{a_i - c_i P_i}, \quad (9)$$

$$Q_i = \frac{d_i + c_i Q_{i-1}}{a_i - c_i P_{i-1}}. \quad (10)$$

When calculating P_{N_x} and Q_{N_x} we get that $P_{N_x} = 0$, $b_{N_x} = 0$. Therefore, T_{N_x} will be equal to Q_{N_x}. Having calculated T_N in this way, one can start the backward-sweep process to obtain T_{N-1}, T_{N-2}, …, T_2, T_1, T_0 [9].

$$T_{i-1}^{k+\frac{1}{2}} = P_{i-1} T_{i-1,j}^{k+\frac{1}{2}} + Q_{i-1}. \quad (11)$$

Based on the above, we can formulate a solution algorithm:

1. We calculate P_0 and Q_0, the coefficients a_0, b_0, d_0 are determined using the initial and boundary conditions.
2. We calculate P_i and Q_i for $i = 1, 2, \ldots, N_x$, using expressions (9) and (10).
3. We suppose $T_N = Q_N$.
4. We substitute T_N into formula (11) and determine T_{N-1}, T_{N-2}, …, T_2, T_1, T_0.

The algorithm for solving equation (3) is similar. The coefficients included in equation (3) will take the following form:

$$a_i = \frac{1}{\frac{\tau}{2}} + \frac{a}{h_y^2},\ b_i = c_i = \frac{a}{h_y^2},\ d_i = \frac{1}{\frac{\tau}{2}}T_{i,j}^{k+\frac{1}{2}}.$$

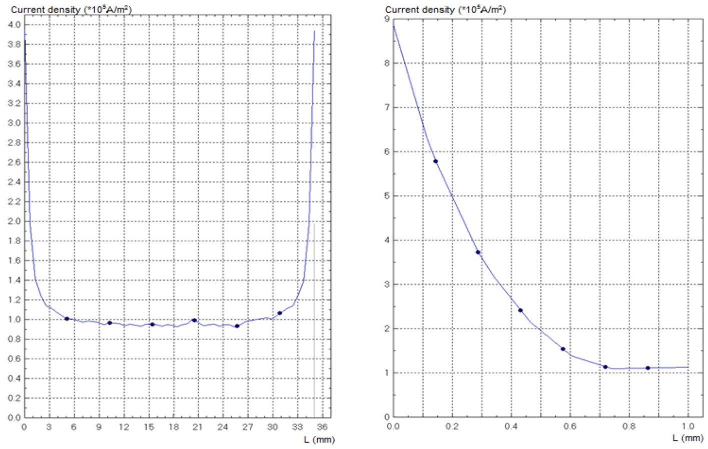
The sweep will be carried out on index *j*.

The Elcut software package was used to calculate the eddy current density distribution in the waveguide pipe and flange. The results confirm the previously accepted assumptions when setting the simulation problem. Fig. 5 and 6 show that the eddy current density increases sharply on the corner surfaces of the pipe and the waveguide flange. In addition, in fig. 5 the eddy current density decreases sharply in the thickness of the pipe and flange walls. Eddy current flow areas are well localized (fig. 6).

Fig. 7 shows the results of heating the waveguide according to the proposed model.

To check the simulation results, the temperature change at control points 1 and 2 was taken (fig. 7). The control points coincide with the points of temperature measurement during the process of heating the waveguide using induction equipment [16; 17].

As it can be seen from fig. 8 and 9, the simulation results quite accurately describe the process of the waveguide elements heating. Consequently, this model can be used to simulate an automated control system for soldering waveguide paths and analyzing control algorithms.



a *b*

Fig. 5. The distribution of pipe eddy current density for the size 35×15 mm:
a – in the large side of the pipe; *b* – in the thickness of the pipe

Рис. 5. Распределение плотности вихревого тока трубы для типоразмера 35×15 мм:
а – по большой стороне трубы; *б* – по толщине трубы

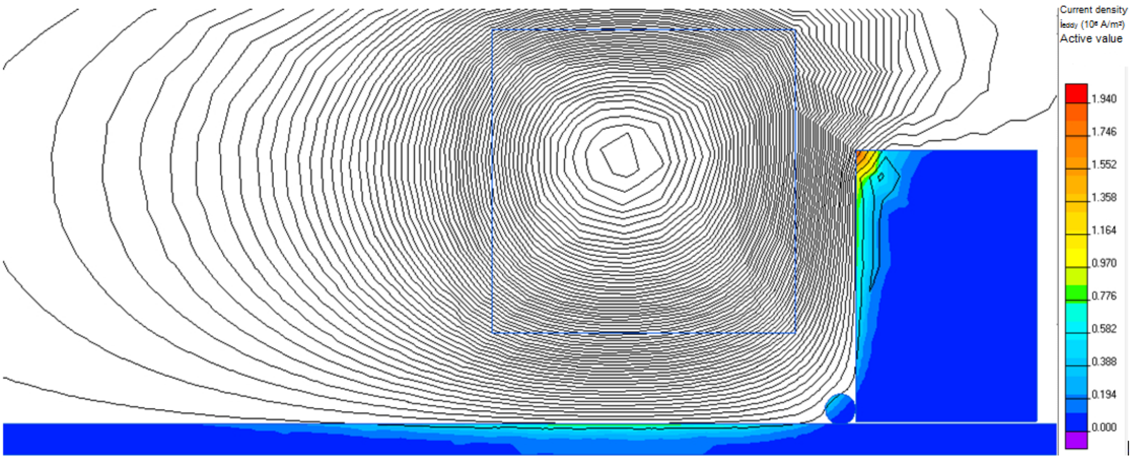


Fig. 6. The distribution of eddy current density in the “inductor – waveguide” system for the size 35×15 mm

Рис. 6. Распределение плотности вихревого тока в системе «индуктор – волновод» для типоразмера 35×15 мм

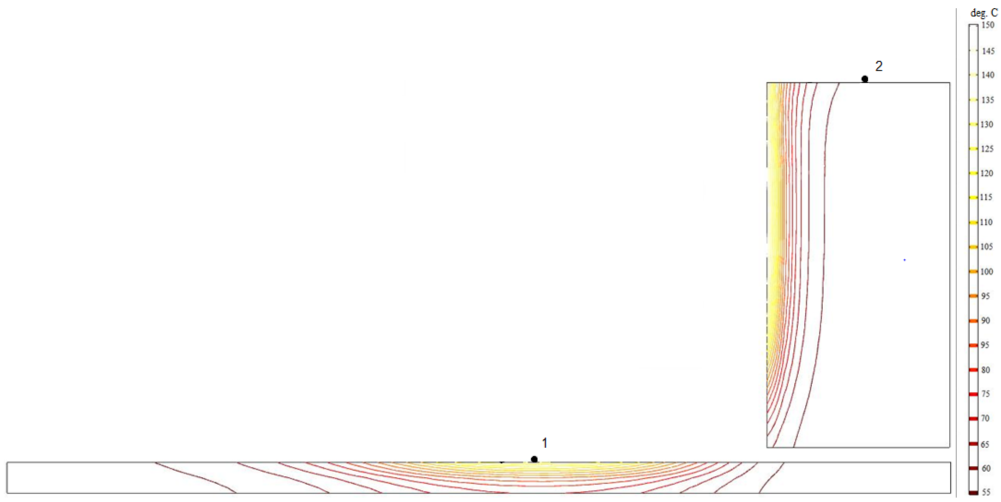


Fig. 7. Temperature fields of the waveguide during induction heating

Рис. 7. Температурные поля волновода при индукционном нагреве

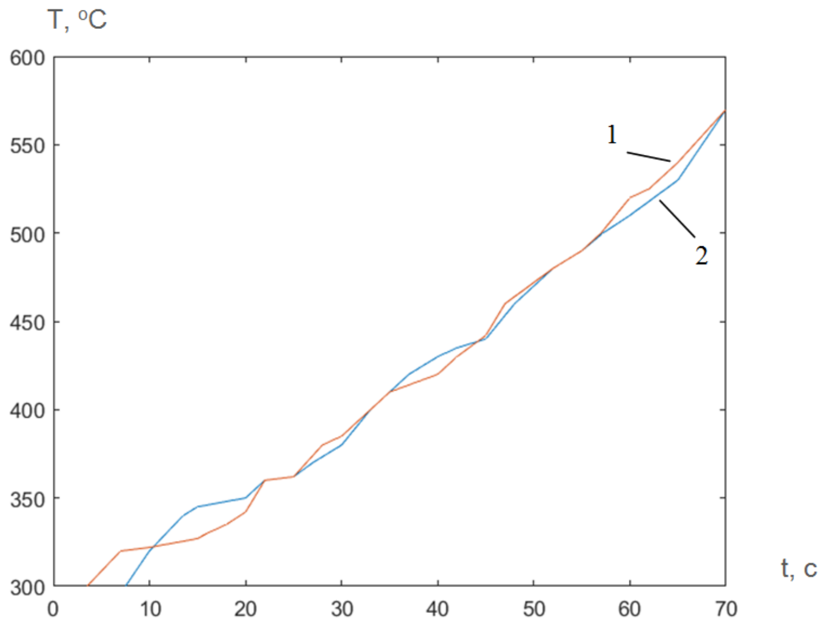


Fig. 8. Heating of the 35 × 15 waveguide pipe:
1 – calculated values; *2* – measured data

Рис. 8. Нагрев трубы волновода типоразмера 35 × 15:
1 – расчетные значения; *2* – измеренные данные

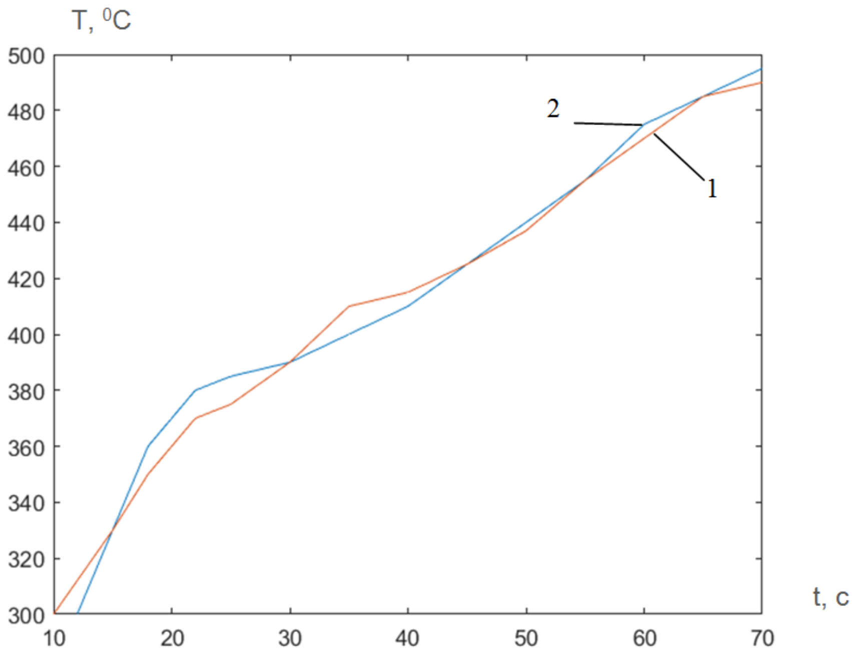


Fig. 9. Heating of the 35 × 15 waveguide flange:
1 – calculated values; *2* – measured data

Рис. 9. Нагрев фланца волновода типоразмера 35 × 15:
1 – расчетные значения; *2* – измеренные данные

Conclusion. 1. The process of induction soldering of waveguide paths has a number of features, which complicates the selection of process parameters for various types of waveguide paths and process control and suggests the need to simulate the heating of waveguides based on the differential equation of heat conduction.

2. To simulate the process of the pipe and the waveguide flange heating, it is most expedient to use the finite difference method.

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