Mathematical model of the waveguide pipe heating in the process of induction brazing

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Abstract. The article presents a mathematical model of pipe heating in the process of induction brazing of waveguide paths. The object of research is the technological process of induction brazing, in particular, the regularities of energy distribution over time over the volume of the pipe Assembly of the waveguide path. The purpose of creating the model is to improve the quality of control of the production process of waveguide paths based on induction heating. The presented models will be actively used in the development of an algorithm for adaptive (intelligent) control of the technological process of induction heating of waveguide path assemblies in order to achieve uniform heating of the brazed elements to form a high-quality one-piece connection.

1. Introduction

The main one’s constructive elements waveguide assemblies the main routes are pipe, as well as flange or coupling. For their connections used methods based on welding or rations. Method creating connections based on induction heating systems are suitable for the solution for this task especially good. Management technological equipment process, in based on which lies induction heating, is that's enough a difficult task, because on the quality issued products it turns out significant impact quantity external and internal factors: evaporation flux in the zone brazing, modification radiative abilities material in the result processes oxidation and etc. The above-mentioned problems of implementation impact on measurement accuracy temperatures product description contactless payments methods. The presence of high requirements to quality surfaces products are made impossible application contact numbers measurement methods temperatures heating the product. Thus, current the task is development mathematical model heating models pipe assemblies waveguide the route.

Modeling technological the process of induction brazing is one of the most simple and effective ways to improve quality control technological process, and as a result increase quality product. Author of work [1-3] submitted technological approach the process of induction brazing for production facilities modular systems solar systems batteries in the form of multiphysical models. Submitted by models can be used for optimization purposes management process induction system brazing by adaptations geometric elements parameters inductor with the goal is more effective and uniform solder heating.

By authors works [4] presented mathematical model of the technological process based on induction heating with using the following parameters: commercial package list Cedrat Flux 10.3. Validity offered model confirmed within the framework of experimental projects research. Results simulations they
agree well with experimental temperature control with a profile in set points on the surface details. Advantage mathematical model the model offered the authors are possibility usage models for forecasting methods these parameters, as a density current and field magnetic field flow inside workpieces, direct measurement which is difficult.

Study [5] shows, what is a reduction order of models is sufficient effective and promising the tool to manage it technological processes induction brazing on the basis of indirect measurements. On the basis of the method orthogonal decomposition Propper was there received the system 4th order. Received information the model provides achievement target temperature, at the same time, its computing complexity that's enough low for her operational solutions with usage that's enough inexpensive the microcontroller. Within the framework of the study [6] developed thermal model technological equipment brazing process infrared by reflow. The model allows you to predict appropriate thermal effects, starting from characteristics convection in the infrared kilns, finish detailed thermal response, including the change solder transition between solid and the liquid phase. Neural network management model technological equipment process induction system brazing is provided in research projects in the field of construction [7-9].

Usage offered by the model's authors allows you to significantly improve the quality management technological equipment process induction system brazing of waveguides interpretation devices. In submitted to the work [10] application neural network models for management technological equipment process repair and maintenance services oil and gas industry equipment. Usage the imitation one simulations for modeling technological equipment process of induction brazing demonstrated in works [11 – 15]. So broad usage the imitation one simulations for optimization purposes technological solutions processes on the based-on induction heating for different industries mechanical engineering allows you to talk about high efficiency this approach for example considered technological solutions processes.

As a tool simulation it was selected the program SimInTech. Its name features that's enough for modeling technological equipment process of induction rations. Except in addition, the given product is available free of charge academic license with insignificant for the solution delivered issues with restrictions. SimInTech it is cross-platform software the product. Also, SimInTech it is a software application product description domestic production.

Application received mathematical models there will be no models used for development the algorithm adaptive (intellectual) management process induction heating assemblies waveguide systems paths with the goal of achievements uniform heating of brazed items elements for formations high-quality all-in-one connections. Working capacity and applicability offered the algorithm will be investigated as in the case of conducting computing resources experiments, so in the process full-scale projects experiments.

2. Materials and methods

To solve the problem of developing mathematical models of induction heating for working out methods for controlling the technological process of induction brazing of waveguide paths, it is necessary to develop mathematical models both for the elements of the waveguide assembly separately and for the entire assembly as a whole. The elements of the waveguide assembly are the tube of the waveguide path, as well as the flange or coupling.

An instant heating source in a flat rod is used as mathematical models for heating assembly elements in order to develop the technological process of induction brazing of thin-walled aluminum waveguide paths (2), (3):

\[ T(x,t) = \int_0^1 \frac{Q}{c\rho F \sqrt{4\pi at}} e^{-\frac{x^2}{4at} - bt} \]  

\[ b = \frac{\alpha}{F} \]
where \( Q \) – amount of heat [J]; \( F \) – cross section of the pipe \([m^2]\); \( x \) – distance from heat source \([m]\); \( c \rho \) - volumetric heat capacity \([J/m^3]\); \( t \) – time \([\text{sec}]\); \( b \) – coefficient of thermal convection into the external environment from the surface of the rod formula (2); \( a \) – coefficient of thermal conductivity; \( p \) – section perimeter.

\[
T(x,t) = \int_{-\infty}^{\infty} \int_{-1}^{1} \frac{Q}{c \rho F \sqrt{4 \pi at}} e^{-\frac{(x-jl-2iL)^2}{4at} - bt}
\]  

(3)

where \( Q \) – amount of heat \([\text{J}]\); \( F \) – cross section of the pipe \([m^2]\); \( x \) – distance from the left end \([m]\); \( c \rho \) - volumetric heat capacity \([J/m^3]\); \( t \) – time \([\text{sec}]\); \( b \) – coefficient of thermal convection into the external environment from the surface of the rod formula (2); \( a \) – coefficient of thermal conductivity; \( p \) – section perimeter; \( L \) – rod length \([m]\); \( l \) – distance from end to source of heating.

3. Mathematical model of the pipe of the waveguide path

For a tube assembly of a waveguide path, one should proceed from the considerations that:

- The tube of the waveguide tract is a rather long body made of a homogeneous material.
- The pipe of the waveguide path has a relatively uniform cross-section along its entire length.
- The pipe of the waveguide path has a similar mechanism of heat transfer and heat conduction.

From which it can be concluded that the mathematical model of a flat heat source in a rod is valid for a flat heat source in a rectangular tube of the waveguide path assembly. Thus, we introduce only a geometric limitation on one side of the rod, thus denoting and considering the limitation of the pipe from the side of the flange protrusion when forming the corresponding connection. Assuming that the waveguide tube is evenly heated over the entire section, since the wall thickness is 2 mm, and the design of the inductor is such that it causes uniform heating around its perimeter. Figure 1 shows a typical waveguide assembly pipe in a realistic image.

![Waveguide Assembly Pipe](image)

**Figure 1.** Photorealistic image of a tube assembly of a waveguide path.

Calculation formula (4) for the process of heating a waveguide tube with reference to a specific standard size in this case is:
\[ T(x,t) = \sum_{j=-1,1} \frac{Q}{F \rho \sqrt{4at}} e^{-\frac{(x+jl)^2}{4at}} e^{-bt} \]  

Figure 2 shows the projections of the tube assembly of the waveguide path with standard sizes.

\[ T(x,t) = \sum_{j=-1,1} \frac{Q}{F \rho \sqrt{4at}} e^{-\frac{(x+jl)^2}{4at}} e^{-bt} \]

Figure 2. The projections of the tube assembly of the waveguide path with standard sizes: where F is the cross-sectional area of the tube; \( p \) - section perimeter.

Figure 3 shows a graph of the heating model of the tube assembly of the waveguide path for different values of the power of the induction heating source.

Figure 3. The graph of the heating model of the tube assembly of the waveguide path: where the blue graph is the temperature of the tube 22x11, heating power 11 kW; orange graph - pipe temperature 22x11, heating power 5 kW; green graph - pipe temperature 22x11, heating power 3 kW.

Thus, this design scheme sufficiently corresponds to the technological process of induction heating for a tube of a waveguide assembly.
4. Experimental study

When conducting experimental studies to assess the quality of the proposed mathematical models of heating waveguide tubes, a series of induction heating of products of various sections and thicknesses was carried out. For illustration purposes, the article chose a standard size of 22x11 mm. The experiments were carried out for different powers of the induction generator: 11 kW, 5 kW and 3 kW.

Figure 4 shows the graphs of induction heating of waveguide tubes, where the solid lines show the temperatures obtained as a result of the simulation, and the dashed lines show the averaged results over 10 full-scale experiments.

![Figure 4](image)

Figure 4. Comparative graph of the model of induction heating and the real technological process of induction heating of the pipe of the assembly of the waveguide path for a standard size of 22x11 mm, where the blue solid graph is the graph of the pipe (model), power 11 kW; orange discontinuous graph - pipe graph (real process), power 11 kW; green solid graph - pipe graph (model), power 5 kW; red intermittent graph - pipe graph (real process), power 5 kW; blue solid graph - pipe graph (model), power 3 kW; brown discontinuous graph - pipe graph (real process), power 3 kW.

5. Conclusion

Within the framework of this study, the problem of developing a mathematical model of induction heating of the flange of the waveguide duct assembly was solved for testing the technological process of induction brazing of thin-walled aluminum waveguide ducts of spacecraft. To verify the developed models, model and field tests were carried out, which showed that the developed model of the flange of the waveguide duct assembly with a high degree of accuracy corresponds to the actual technological processes of induction brazing of thin-walled aluminum waveguide ducts of spacecraft.

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