**Induction heating simulation of the waveguide assembly elements**

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**Abstract.** The waveguide path systems consisting mainly of aluminum alloys with improved weight, size, and electrical parameters are used to ensure the functioning of the spacecraft and its onboard equipment in accordance with a given program. When assembling the elements of the waveguide paths, in particular a thin-walled pipe of rectangular cross section, coupling and flange, induction brazing is used. Element-by-element assembly of lightweight waveguide paths using the method of induction soldering is connected with a number of technological difficulties such as the uneven distribution of temperature fields, the thickness variation of the soldered products and the design features of the inductors. This paper presents a model describing the process of heating a pipe-inductor system during induction brazing. The presented model describes the process of induction heating of the pipe as a separate structural element of the waveguide path. In the process of simulation in the Comsol software, on the basis of numerical simulation methods with the connection of the necessary media involved in induction heating, the pipe heating graphs are obtained.

1. **Introduction**
The waveguide systems consisting mainly of aluminum alloys with improved weight and size and electrical parameters are used to ensure the functioning of the spacecraft and its onboard equipment in accordance with a given program.

When assembling the elements of the waveguide paths, in particular the thin-walled tube of rectangular cross section, coupling and flange, induction brazing is used. The use of this method of soldering allows obtaining soldered joints of waveguide tubes with a wall thickness of 0.5 mm with more massive flanges (up to 7 mm thick), couplings and corners.

Induction brazing of thin-walled waveguide paths from aluminum alloys is a complex technological process, which has several features such as [1]:

- a small difference in the melting points of one of the applied solders form silumin and the melting point of the base material of the assembly elements, with an average induction heating rate of 10–15 °C/s, this requires accurate testing and reproduction of technological regimes;
- the elements of the waveguide assembly are heated independently of each other, i.e. there is practically absent to transfer between them due to heat conduction up to the moment of solder melting;

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• the thickness variation of the brazed products, the dimensional tolerances of the used particularly thin-walled waveguide tubes (wall thickness from 0.5 mm) lead to a difference in the mass of the like items up to 25% (for waveguide pipes);
• aluminum alloys used for the production of waveguide path elements practically do not change color during the heating process, which makes it impossible to visually monitor the presence of local overheating of the brazed products;
• due to some facilities of an induction heating of the zone with the maximum density of induced eddy currents, and, consequently, the zone of maximum heat generation in sections of the soldered elements of the waveguide paths do not coincide with the soldering zones;
• equable heating of the soldered elements is ensured by selecting the optimal technical parameters of the equipment, especially as regards the shape of the inductors and the operating frequency and power of the generator.
These factors significantly complicate the development and subsequent reproduction of the technological process of induction soldering, affect the stability of the quality of products, require highly skilled personnel involved in the production.
To reduce the influence of these features of the process of induction soldering, it is necessary to automate this process. Though for the development of an automated process control system for induction soldering, it is necessary to fully and clearly understand the process of soldering the assembly of waveguide paths, especially since this design consists of separate structural elements, such as a pipe and a flange / coupling.
Based on the foregoing, it is necessary to develop a number of mathematical models describing induction heating of individual structural elements of the assembly of the waveguide path and the product as a whole.

2. Scientific literature review
The results, techniques, and methods of mathematical simulation of induction heating, a channel of penetration, and heat transfer during induction brazing are widely used in the literature.
In one of the scientific paper mathematical simulation and optimal control of induction heating are considered by V. Rudnev [2]. Other scientists such as E. Rapoport, Y. Pleshivtseva studied the method of calculating the optimal processes of induction heating of metals, managing the processes of static induction heating and progressive and continuous processes [3]. J. Kapusta, J. Camber, G. Hulkó conducted a numerical simulation of modular industrial induction heating of steel blanks for hot forming using COMSOL software with the presentation of the basic model based on the finite element method [4]. A mathematical simulation of temperature for MSD for elevated temperature NDT application is presented in the papers by B. Patidar. This paper considers a simulation of the electromagnetic field using the formula of magnetic vector potential, heat transfer is represented using the Fourier equation. Temperature-dependent material properties, such as electrical conductivity, magnetic permeability, specific heat capacity, thermal conductivity, are considered by B. Patidar, M.M. Hussain, Sanjoy Das, D Mukherjee, A.P. Tiwari [5].
The group of German scientists in their work [6] applied the formal Lagrangian to the optimal control problem of the process of induction heating, this is shown that how a gradient algorithm in combination with FEM software can be used for numerically solving the optimality conditions consisting of the partial differential algebraic equations of several coupled physical domains in a straightforward manner.
The Russian scientists are V.I. Luzgin, A.Yu. Petrov, V.A. Prakht, and F.N. Sarapulov investigated to construct the interrelated nonlinear electromagnetic and thermal models of processes arising when the moving steel round billets undergo thermal heating [7].

3. Simulation of waveguide pipe heating
For the initial assessment of the induction soldering process of waveguide paths, the authors use the software product COMSOL Multiphysics. This software permits to move from simple models to more
complex volumetric models. It permits to take into account all features of the heating process. The authors start with the simplest element of the waveguide assembly to the pipe.

The pipe-inductor system is considered by Figure 1. The process of soldering the waveguide occurs when selecting the minimum gaps between the waveguide and the inductor. The minimum values of the gaps of the technological problem between the inductor and the waveguide are the gaps h1 and h2 from 1 to 2 mm [8].

![Figure 1. Technological gaps between the inductor and waveguide elements during soldering](image)

The simplified visual multiphysical model is constructed for the preliminary analysis of induction heating in the "pipe to inductor" model. This system will be presented in the form of a two-dimensional model. The first stage begins with a description of the geometry and materials. The selected geometry presented in Figure 2 is composed from a rectangular inductor and a pipe.

After that, each item was assigned its own material. For the inductor, the copper element (Copper) was chosen from the materials library, the waveguide is selecting an element that meets the characteristics of aluminum AD31, the international analogue Aluminum 6063-T83 is presented in the material library Comsol, which satisfies the properties of aluminum for the manufacture of waveguide paths.

To fill the cavities h1 and h2, as well as the cavities inside the pipe, it is necessary to select the necessary air element from the material library without changing the default parameters. The ambient temperature is 293.15 Kelvin.

![Figure 2. Geometry of the pipe - inductor model (view from above)](image)

To calculate the model, the authors use the Induction Heating multiphysical interface “Induction Heating”; two physical interfaces are automatically added to the model: Magnetic Field and Heat Transfer in Solids (Heat Transfer in Solids). The multiphysical connections describe the dissipation of electromagnetic energy as a source of heat and, in addition, the dependence of the electromagnetic properties of materials on temperature can be specified [1]. Accounting for the relationship between phenomena provides a pre-selected type of study: Coil Geometry Analysis, Stationary.
For the task “Magnetic Field” the authors configure it as follows: in the automatically added system Ampère's Law set all the default parameters for the selected material. In this case there are an outer boundaries of the inductor and inner boundaries of the waveguide pipe. In “Initial Values” the authors select all available domains: inductor, air layers in the gap between the pipe and the waveguide itself, in the Coil parameter set the Model Input values.

The type of material is represented by the characteristics of copper. In “Conductor Model” the authors select “Single conductor”, the coil current is 150 A, in “Conduction current” the authors select the values “From material”.

The simulation results are following the density distribution of the magnetic flux when performing induction soldering is presented in Figure 3. The model was calculated using the Frequency domain quotient, at a given frequency $f = 66000\text{Hz}$.

![Figure 3. Magnetic flux density distribution](image)

Induction heating was calculated by two solvers, such as Coil geometry analysis, which is responsible for calculating the current flowing in the coil, and Time dependent time solver, which permits to set a certain period of an induction heating and build a thermal model.

The finite element grid must be set for performing calculations. This grid should be small enough to ensure the accuracy of the calculation. This type of grid “The Boundary Layers” is fit (Figure 4).

The authors apply it to the inductor and the pipe with the additional purpose DeltaCu and DeltaAl, respectively. This grid is made more densely in the area of heating to improve the accuracy of calculations [9].

![Figure 4. Grid of simulation](image)

The results of twenty-second heating of the aluminum waveguide are shown in Figure 5. It can be seen that the waveguide is not uniformly heated, i.e. the density of the magnetic field is higher here. This is due to the fact that the waveguide is located close to the conclusions of the inductor. It is confirmed by experimental studies.
Figure 5. Process of induction heating of the waveguide a: at t = 5, b: at t = 20 sec

The density of the distribution of eddy currents in the pipe-waveguide system is shown in Figure 6.

Figure 6. Distribution density of eddy currents in the pipe to inductor system

4. Discussion
The electrothermal processes occurring in the object under study depend mainly on the external magnetic field. Therefore, for correct description, it is necessary to consider the cumulative system of a source of an alternating magnetic field and a body subjected to heating under the action of a field.

The source of the electromagnetic field in induction heating installations is an inductor, the design of which determines the physical processes in the electromagnetic system of the induction heater, technical characteristics and energy indicators of the heating process.
In a simplified form (without considering the power section of the induction equipment), the system is an inductor with an assembly unit placed in it. To reproduce the soldering process, it is necessary to accurately position the waveguide relative to the working window of the inductor.

The absolute value (norm) of the calculated current density and the magnetic induction lines constructed in Figure 3 and 6 show that the maximum current density is located inside the coil regions. The current density distribution in the cross section of the coil is not equable. The current flows mainly in the inner part of the inductor coil. It is possible to notice that a strong current flow through the coil, but the temperature is close to the ambient temperature due to water cooling. On the other hand, the temperature of the metal due to eddy currents and Joule heat approaches close to the melting point of the metal. The inductor geometry can be adjusted to various design constraints [10, 11]. The properties of the inductor coil and the geometry of all the objects of the model were presented as simply as possible in order to reduce energy consumption and provide controlled metal melting.

5. Conclusion
Element-by-element assembly of lightweight waveguide paths using the method of induction soldering is connected with a number of technological difficulties such as the uneven distribution of temperature fields, the thickness variation of the soldered products and the design features of the inductors. The considered process of simulation induction heating based on a two-dimensional pipe-waveguide model in the COMSOL Multiphysics software permits to estimate with sufficient certainty the processes occurring during induction brazing of waveguide paths. The presented model describes the process of induction heating of the pipe as a separate structural element of the waveguide path. In the process of simulation in the Comsol software, on the basis of numerical simulation methods with the connection of the necessary media involved in induction heating, the pipe heating graphs were obtained.

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