Control of the technological process of the waveguide paths induction soldering in the framework of Industry 4.0

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Abstract. The control of the induction soldering technological process is significantly complicated by the presence in the heating zone of physical phenomena that make it difficult, and sometimes completely impossible, to measure the temperature in the heating zone using non-contact temperature sensors. At the same time, the use of contact sensors is also difficult in the production of spacecraft’s elements due to the high requirements for the quality of the product surface, as well as the high time required for the installation of contact sensors and the human factor. This paper presents the concept of a cyber-physical system for controlling the technological process of induction soldering of spacecraft waveguide paths in the framework of Industry 4.0, which is actively developed at the enterprises of the rocket-space complex. As a part of this concept implementation, it is proposed to develop mathematical models for each element of the waveguide assembly separately, and for the entire assembly of the waveguide path. The use of mathematical models developed within the framework of this concept will make it possible to improve the quality of the induction heating process control using adaptive and intelligent methods.

1. Introduction

Technological processes based on induction heating are widely used to create permanent connections in various fields of domestic and international engineering, including the aerospace industry. Improving the quality of technological processes of induction soldering is the main factor in achieving a sufficiently high quality of products, as well as improving labor productivity.

It is advisable to control such a process using two control loops. The first loop is control by the position of the workpiece in the inductor window. The second loop is control by the power of the induction heating generator. Primary control loop is aimed at determining where the energy of the electromagnetic field is applied to prevent overheating or overcooling of one of the waveguide path assembly elements.

When controlling by heating power, the point of information collection about the technological process does not change. The measurements are taken at the same place. However, when controlling along the second circuit (the position of the workpiece relative to the inductor frame), the information pickup point for the pyrometer directed to the pipe changes. For the pyrometer directed to the flange, the pickup point does not change. Due to the fact that it is impossible to move the pyrometer aimed at
the pipe together with the workpiece, there will be areas where the target indicator of the pyrometer intersects with the inductor.

Secondary control loop is responsible for the intensity of the applied magnetic field at the selected location of the waveguide assembly. The control of the induction soldering process is significantly complicated by the presence in the heating zone of physical phenomena: the evaporation of the flux and the change in the material’s emissivity. This makes it difficult to measure the temperature in the heating zone using non-contact temperature sensors.

The use of contact sensors is difficult in the production of the spacecraft’s elements due to the high requirements for the product’s surface quality as well as the high time required to install contact sensors and human factor. It leads to the inability switching to the concept of cyber-physical systems process control in the framework of Industry 4.0, which is actively developing at the enterprises of the space-rocket complex.

2. Literature review

The method of creating permanent joints based on induction heating is widely used in various fields of mechanical engineering [1], [2], [3], [4], [5], [6], as well as in many other areas [5], [6], [7], [8], [9], [10].

The authors of [11] developed automated equipment and technology for induction soldering of aluminum waveguide paths of spacecraft. The software of this system is an implementation of the proportional-integral-differential (PID) controller. This control method does not provide sufficient quality. The main difficulty is the initial setup of the process. This is explained by the influence of the human factor at the stage of setting up the process by the technologist. Incorrect adjustment of the technological process initial parameters of the waveguide paths induction soldering does not allow predicting the result of the automated system. During experimental studies of this technological process, it was found that software control of the heating power allows us to control only one parameter - the temperature of the waveguide tube. The temperatures of the flange and the waveguide tube can vary significantly. The correct choice of the position of the workpiece relative to the plane of the inductor can reduce the temperature difference in the region of the solder melting temperature. In the manufacture of waveguide path assemblies, pipes with a thickness difference of up to 20% are used, so it is impossible to completely exclude the temperature range. This problem is solved by automated regulation of the distance from the flange to the inductor during the induction soldering. Improving the quality of the induction soldering control, the implementation of a second control loop was achieved [12]. Also, various non-standard errors caused, for example, by the influence of flux [13], the degree of influence of which can be reduced using intelligent methods [14], [15], have a rather strong influence on the quality of process control.

The most suitable intelligent methods for controlling the technological process of induction soldering of thin-walled aluminum waveguide paths are: artificial neural networks, a fuzzy controller, as well as a neuro-fuzzy controller.

Numerous studies show that the use of intelligent methods allows us to achieve higher results than the use of classical control methods. Artificial neural networks are used to solve various problems related to control, classification, clustering, etc. In [16], an artificial neural network with a radial basis function was used to determine the stability range region of the generator steady state with a variable load in order to observe the effect of load changes. Artificial neural networks have proven themselves well for modeling and controlling complex objects, such as ultrasonic motors [17], compensating voltage harmonics in an electric power distribution system [18], and controlling photovoltaic systems [19], [20]. Systems based on fuzzy logic are also widely used to solve control problems. In [21], a fuzzy controller is used to manage a permanent magnet synchronous motor. In this work, a fuzzy controller is used in the speed loop instead of the traditional proportional-integral (PI) controller. The authors of [22] use fuzzy logic controllers to track the maximum power of the wind generator and balance energy consumption. Methods based on neuro-fuzzy controllers use the strengths of both artificial neural
networks and fuzzy logic methods. Examples of using this method are: a car control system [23], an air conditioning control system [24], and a step-up DC converter control.

3. Concept of the control system
The aim of the study is to increase the efficiency of the induction soldering process by introducing adaptive (intelligent) control methods, developed using mathematical models obtained in the framework of this study. To achieve this goal, it is necessary to solve the following problems within the framework of the concept:

- Problem of accurate mathematical modeling of the magnetic field for inductors of various sections and linear sizes.
- Calculation of instantly input energy generated by the inductor’s magnetic field.
- Calculation of the energy distribution over the volume of waveguide path’s soldered elements, taking into account their different geometry, thickness and convection cooling.
- Development of mathematical models both for each element of the waveguide assembly separately, and for the entire assembly as a whole.
- Verification of models using modern modeling tools (Matlab, Ansys, etc.), as well as during field experiments.
- Development of adaptive (intelligent) methods for controlling the process of induction soldering [25].
- Development of the control system prototype for the induction soldering of waveguide paths using developed mathematical models and algorithms.
- Verification of the operability, applicability and effectiveness of the prototype both when conducting computational experiments, and in the process of full-scale experiments [26].

Thus, to increase the efficiency of the induction soldering process, it is proposed to develop a model-algorithmic apparatus that will form the basis of modern automated control systems of the induction soldering at aerospace manufacturing enterprises. The structure of the induction soldering automated control system is shown in figure 1.

![Figure 1. Structure of a cyber-physical induction soldering process control system.](image-url)
As a part of the research, a set of new mathematical models of heat distribution in the assembly of waveguide paths will be developed, which will allow for optimization of soldering modes. Such models will take into account not only the characteristics of the materials being joined, but also the technological parameters of the induction soldering process.

The developed models for optimizing soldering modes will take into account the nature of the heat distribution in the penetration zone, the established technological parameters of the induction soldering process, as well as the required parameters of the soldered connection of the waveguide path assemblies.

All proposed models have to be implemented as part of the prototype software system for the automation of induction soldering and investigated on industrial samples of waveguide path assemblies. This will allow formulating recommendations for the further implementation of research results at aerospace enterprises.

A block diagram of a system that implements the proposed concept is presented in figure 2.

**Figure 2.** Block diagram of a cyberphysical induction soldering process control system.

In general, to solve the problems of scientific research, it is supposed to use approaches developed in the framework of the theory and practice of system analysis, the theory of mathematical modeling of thermal processes, the theoretical foundations of computer science, as well as the theory of automatic control. To carry out a theoretical and analytical review of the approaches used to simulate the thermal processes that occur during induction soldering, it is proposed to use methods and means of scientific knowledge and patent search.
To develop models for soldering modes optimizing, it is proposed to use a system modeling apparatus and optimization theory. When developing a prototype of a software system using the obtained models and algorithms for controlling soldering modes, it is proposed to use programming technologies and methods, software development technologies and automated systems. In the process of experimental studies of the proposed approach on industrial samples of waveguide path assemblies, a mathematical statistics apparatus will be used to evaluate the effectiveness of the developed model and algorithmic apparatus, including checking the reproducibility criteria of the results.

4. Conclusion
In the framework of this study, the concept of a cyber-physical system for controlling the technological process of induction soldering of spacecraft’s waveguide paths in the framework of Industry 4.0 is presented. In the process of further research, mathematical models will be developed both for each element of the waveguide assembly separately, and for the entire assembly of the waveguide path.

Using the obtained mathematical models, algorithms for adaptive (intelligent) control of the induction heating process will be developed in order to achieve uniform heating of the soldered elements to form a high-quality one-piece connection.

It is also proposed the development of the control system prototype for the induction soldering of spacecraft’s waveguide paths using developed mathematical models and algorithms, the operability and applicability of which will be investigated both during computational experiments and in the course of full-scale experiments.

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