Complex of automated equipment and technologies for waveguides soldering using induction heating [1]

A V Murygin, V S Tynchenko, V D Laptenok, O A Emilova, A N Bocharov

Reshetnev Siberian State Aerospace University 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russian Federation

E-mail: vadimond@mail.ru

Abstract. The article deals with the problem of designing complex automated equipment for soldering waveguides based on induction heating technology. A theoretical analysis of the problem, allowing to form a model of the «inductor-waveguide» system and to carry out studies to determine the form of inducing wire, creating a narrow and concentrated heat zone in the area of the solder joint. Also solves the problem of the choice of the temperature control means, the information from which is used later to generate the effective management of induction soldering process. Designed hardware complex in conjunction with the developed software system is a system of automatic control, allowing to manage the process of induction heating, to prevent overheating and destruction of the soldered products, improve the stability of induction soldering process, to improve the quality of products, thereby reducing time and material costs for the production.

Introduction

The waveguide systems are widely used in communication systems of spacecraft, ensuring the functioning of the apparatus and its on-Board equipment [1, 2].

However, induction soldering of thin-walled waveguides is a complicated technical process with a number of features [3].

Firstly, applied silumin solder has a melting temperature close to the melting temperature of the basic material. At speed induction heating 10 – 15 °C/sec an exact observance of the technological mode of the soldering process is required. Secondly, the component parts of a waveguide system such as a waveguide tube, flange or coupling in induction heating process are independent systems up to the point of melting solder between them [4]. That is, between the elements the heat exchange is practically absent, and their heating occurs independently from each other. Thirdly, it was found that during induction heating of the waveguide tracts of the maximum heat generation in the sections of elements zone (maximum density of induced eddy currents) do not coincide with the zones of the soldering [5].

In addition, a large range of brazed products with different mass-dimensional parameters leads to a difference in weight of similar products up to 25%. Also, during the heating elements of the waveguide tracts do not change color, eliminating the visual control of local overheating of solder products [6].

These factors significantly complicate the reproduction of the technological process of induction soldering of waveguide tracts, make demands on the requirements for accuracy in positioning the

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products, to form the inductor, the parameters of the generator equipment for induction soldering and require highly skilled personnel [7, 8].

Analysis of the above listed features of induction soldering revealed the need to automate the process, and led to the creation of a hardware-software complex, allowing to accurately reproducing the process.

1. The theoretical analysis of the problem

When considering the specific physical processes as an object subjected to the induction heating, a compound of straight section waveguide tube and the flange has been chosen (Fig. 1). Selection of an object is related to its prevalence. The dependences obtained during the carried out research with minimal assumptions are valid also for all other areas of the waveguide tract subjected to the induction heating. The obtained dependences are important for understanding the physical processes in real objects.

Electrothermal processes occurring in the subject depend mainly on the external magnetic field, so for their correct description the aggregate system which consists of the alternating-current magnetic field source and the object subjected to heat under the effect of the field, should be considered. In simplified form (without considering the power of the induction equipment) system is represented by the inductor with an assembly unit placed in it (Fig. 1). The considered system is called «inductor – waveguide».
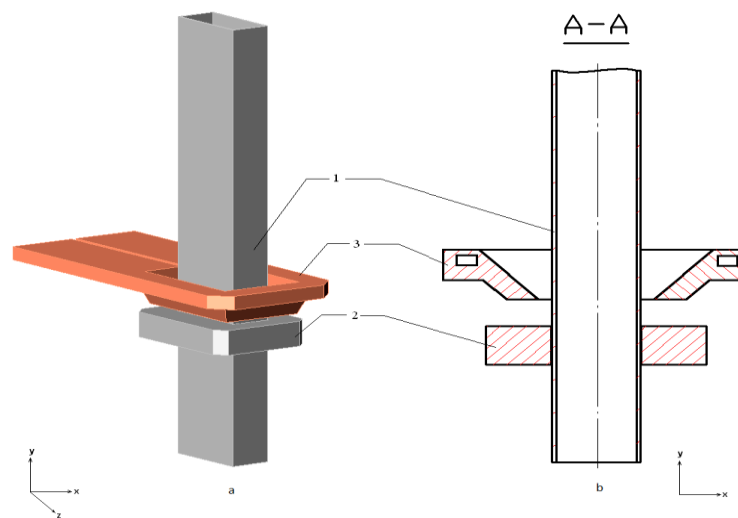

Figure 1. System of interest «inductor – waveguide»
1 - waveguide tube; 2 - flange; 3 - inductor

The mathematical model of this system is built without significant errors based on the following assumptions:

- the spatial configuration of the system allowed to restrict the consideration of the two-dimensional plane-parallel field (x, y), it was assumed that the geometry of the calculating areas, properties of environment and parameters characterizing the sources of the field remain unchanged in the direction of the z-axis (Figure 1 b);

- the field is considered to be quasi-stationary; the average frequency of the external current 65KHz allows to neglect the bias currents as compared with the currents in the conductive bodies;

- hysteresis losses are not accounted, because of their insignificance in comparison with the losses from eddy currents.

Analysis of alternating currents magnetic field consists of the calculation of the electric and magnetic field excited by an alternating current. The problem is formulated as a differential equation in partial derivatives relatively to the complex amplitude of the magnetic vector potential, recorded as:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu_y}\cdot\frac{\partial}{\partial x}A\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu_x}\cdot\frac{\partial}{\partial y}A\right)-i\omega\gamma A=-j \quad ,$$

The heat equation is used during solving the thermal problems:

$$\frac{\partial}{\partial x}\left(\lambda_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y\frac{\partial T}{\partial y}\right)=-q-c\rho\frac{\partial T}{\partial t} .$$

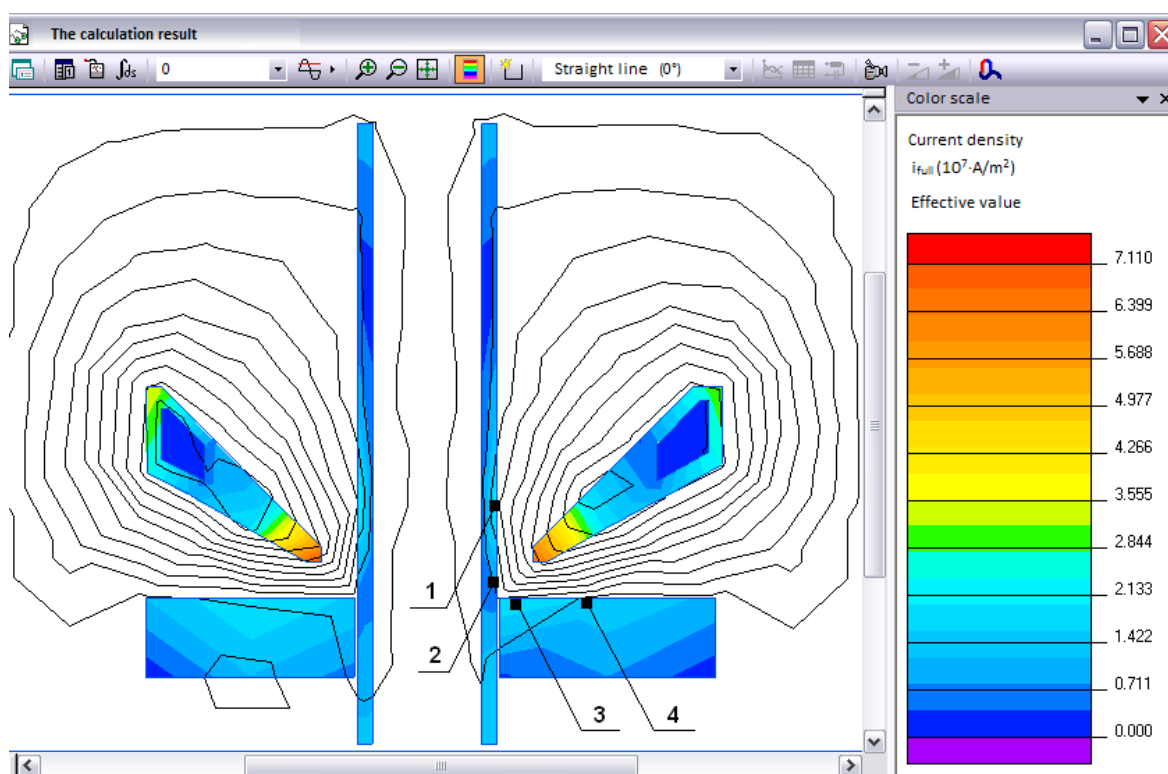System model «inductor – waveguide» built with the help of software package Elcut, is shown in Figure 2.

Figure 2. Model «inductor – waveguide» system
1,2,3,4 – the characteristic point limiting the soldering zone

On the basis of the obtained model research for the problem of the thin-walled rectangular pipe and flange heating in the process of heating during soldering was conducted. Local values of the various physical quantities, obtained in 4 characteristic points (Fig. 2) limiting the soldering zone are summarized in the Table 1.

As seen in the Figure 2 and Table 1, the maximum density of the eddy current, and hence the maximum heat radiation were observed at characteristic points 1 of the tube and 3 of the flange located in the soldering zone.

Table 1. Local values of physical quantities in the characteristic points of the research system.

Physical quantities	Point 1	Point 2	Point 3	Point 4
Induction B, 10^{-3} T	27,809	16,039	6,363	5,853
Strength H, $10^3 \cdot$A/m	9,6216	5,5494	2,2015	2,0253
Current density $i_{full.}$, $10^7 \cdot$A/m^2	2,1256	2,0732	1,9225	1,4784
Current density $i_{eddy..}$, $10^7 \cdot$A/m^2	2,1256	2,0732	1,9225	1,4784
Heat radiation Q, $10^7 \cdot$W/m^3	1,2211	0,14985	8,606	0,59069
Energy density W, J/m^3	133,78	44,504	4,2307	5,9277

As result of the conducted research the inducing wire shape was specified (Fig. 2), which allows to bring the inductor closer to the soldering zone, to create a narrow and concentrated heat zone eliminating overheating and destruction of the products outside the soldering zone, that provides high energy efficiency of the «inductor – waveguide» system.

2. Technological solutions
Let's consider the basic requirements for a technological process of assembling the elements of the waveguide paths by inductive soldering and induction equipment with high energy efficiency development and modernization by using high-tech means of pyrometry for implementing the robust feedback in control systems.

2.1 Inductor
Based on the thermal fields modeling a set of inductors for soldering lightweight waveguide tracts of different sections was developed. The proposed design of inductors provides equal distribution of temperature fields along the perimeter of the heated products in the soldering zone with the required accuracy (± 5 ° C), and also it provides the combination of maximum energy density zones with soldering area, which eliminates the possibility of overheating and destruction of soldered product outside of the soldering zone. Control of the temperature distribution along the contour of the heating carried out by means of thermocouples and pyrometers. General view of the inductor for soldering waveguide tubes with a cross section of the waveguide channel 19×9,5 mm is shown in Figure 3.

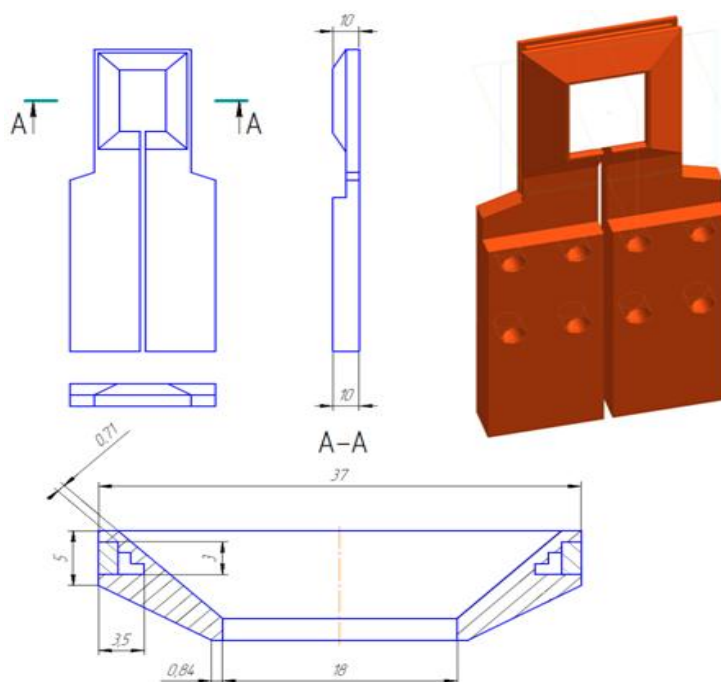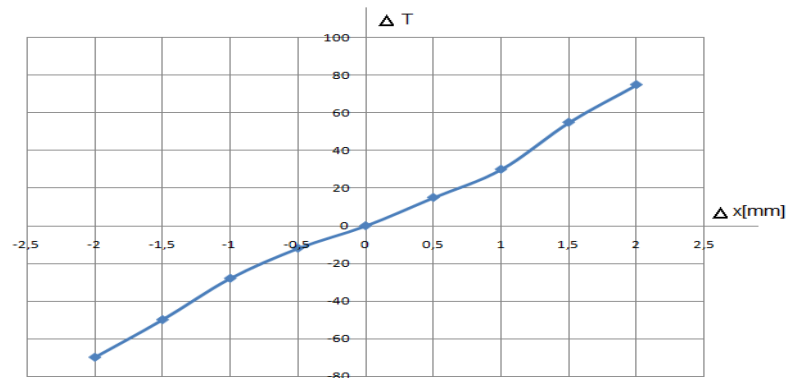**Figure 3.** Inductor with optimal performance heating

2.2 Manipulator
To estimate the margin of error for the positioning of the waveguide in the inductor experimental research of the dependence of temperature gradient along the perimeter of the heated products in soldering zone from the displacement of the heated product relative to the inductor was conducted (Fig. 4). The data obtained in experiments show the need to position elements of waveguide tracts relative to inductor with an accuracy of at least ± 0.3 mm.

Figure 4. The dependence of the waveguide tube temperature gradient from the waveguide offset relative to inductor

Based on the experience of industrial applications of various devices and manipulators, which can be used for positioning elements of the waveguide tracts during soldering, as well as on the basis of the requirements of positioning accuracy (±0,3 mm), manipulator with enhanced functional characteristics was designed (Fig. 5).
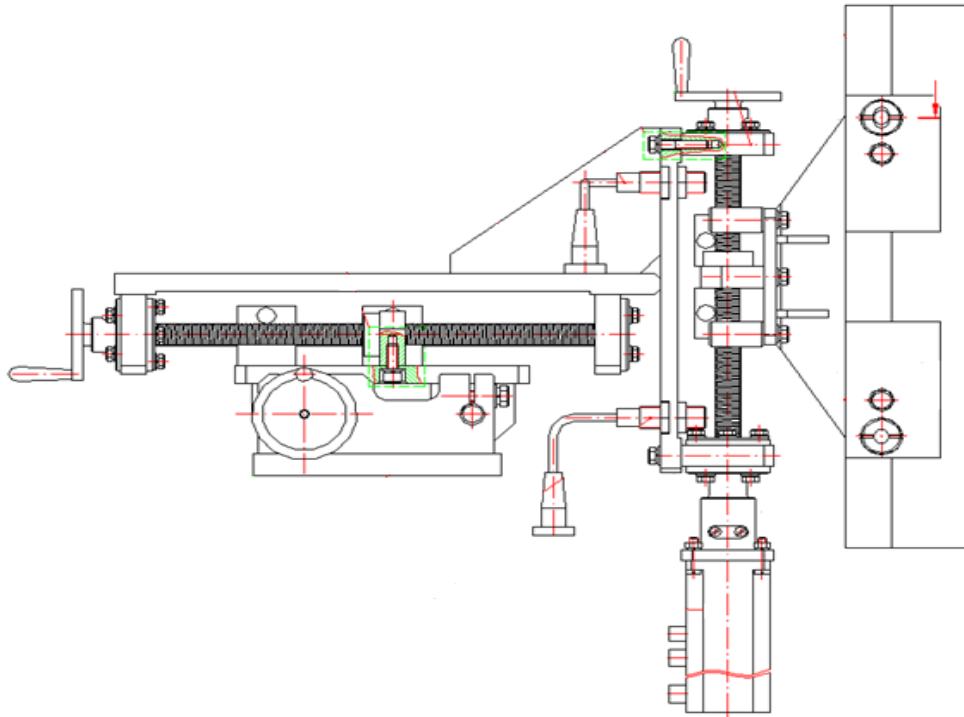
Figure 5. Manipulator with improved functional characteristics

The manipulator is equipped with displacement nodes with minimal backlash, which allows to position the soldered product with accuracy of ±0.1 mm relative to the inductor. Capture device of soldered parts and all the massive manipulator parts, that are located in close proximity to the inductor, are made of heat-resistant dielectric material. This allows to minimize the distortion of the inductor magnetic field, and, therefore, to provide a symmetrical distribution of temperature fields in soldered products. Electromechanical drive of the manipulator allows integrating it into the automated control system, with ability to the automated changing of position of the heated products directly in the soldering process.

2.3 Tools of temperature control

Decision about the use of contactless pyrometric sensors was made while development of the automated equipment complex. The main requirements for the choice was the high temperature control precision (not less than 0.5%), controlled spot's diameter not more than 1.5 mm. (to control the temperature in the gap of the inductor-waveguide), electromagnetic interference immunity and pair it with a computer.

Pyrometer AST 250 was selected as contactless temperature sensors because it satisfies the above listed requirements.

Four pyrometers were used in the study of thermal fields of the waveguides' elements, induced by the inductor (Fig. 3). As result of the conducted research it was determined that 2 pyrometers are enough for the automation of the induction soldering of waveguide tracts' elements process, one of which is used for temperature control on the waveguide flange and the other – on the waveguide tube.

2.4 Software of automated equipment complex

The soldering process programming consists of the specifying of the linear law of the waveguide tube temperature rise with subsequent stabilization of its temperature in the characteristic point above the melting point of the solder but below the melting temperature of the waveguide material.

A software product used to automate the process of induction soldering is a Windows-application, which work is possible in systems like Windows XP/7/8/8.1/10 [9].

It is programmed in C++ in the programming system Borland C++ Builder 6.0 using an object-oriented approach. Work with COM ports is implemented through WinApi, work with board PCI-1710 is implemented through third-party libraries bdaqctrl.h.
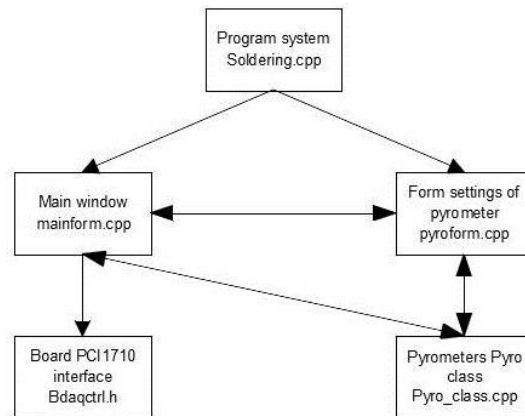

Figure 6. Software structural scheme

The software of control system allows defining the heating law of soldered elements of waveguide tracts to ensure required temperature distribution on the heated objects (Fig. 7), high quality of the soldering joints, eliminating the possibility of the overheating and destruction of the heated objects.
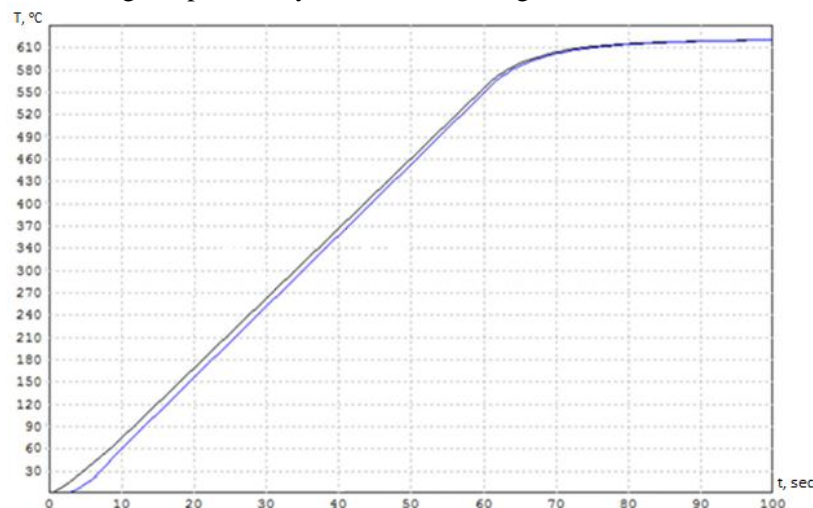

Figure 7. Law of temperature distribution in two characteristic points of the heated object with stabilization of temperature in the region of 600 ± 5 °C

3. Automated control system
A new double-circuit functional scheme of the automated control system of the induction soldering of the spacecraft (SC) antenna-feeder devices (AFD) elements (Fig. 8) process is developed, allowing to perform the heating of the waveguide tracts elements according to a given law by changing the power supplied to the inductor and the distance from the inductor to the heated product, providing the desired temperature distribution on heated objects (Fig. 7).
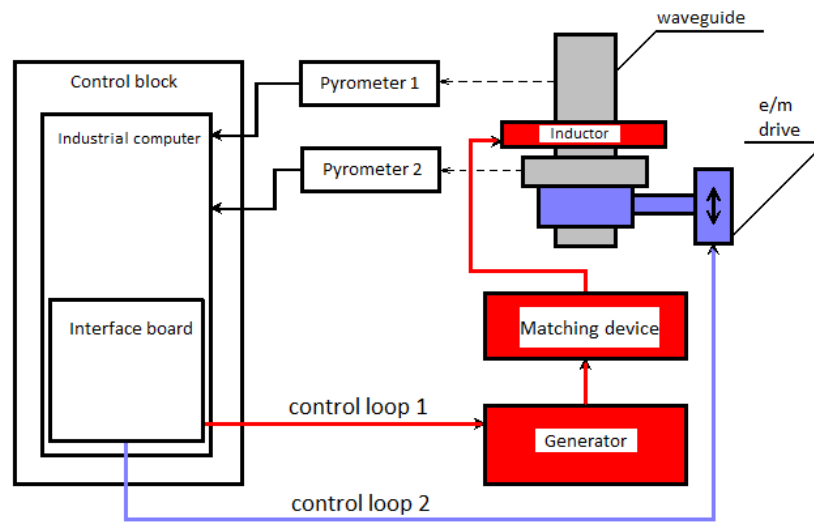
Figure 8. Structural scheme of the automated equipment complex.

The circuit 1 provides control of power supplied to the inductor. The contour 2 – control of the electromechanical manipulator drive – allows to change the position of the soldered waveguides elements relative to inductor. Control of the process technological parameters is performed by computer by using error signals obtained as a result of the comparison of the program temperature with pyrometers controlling temperature of waveguide tube and flange registrations.

4. Complex equipment

General view of working area of the automated equipment complex is shown in the Figure 9 [10], and general view of the entire complex is shown in the Fig.10.
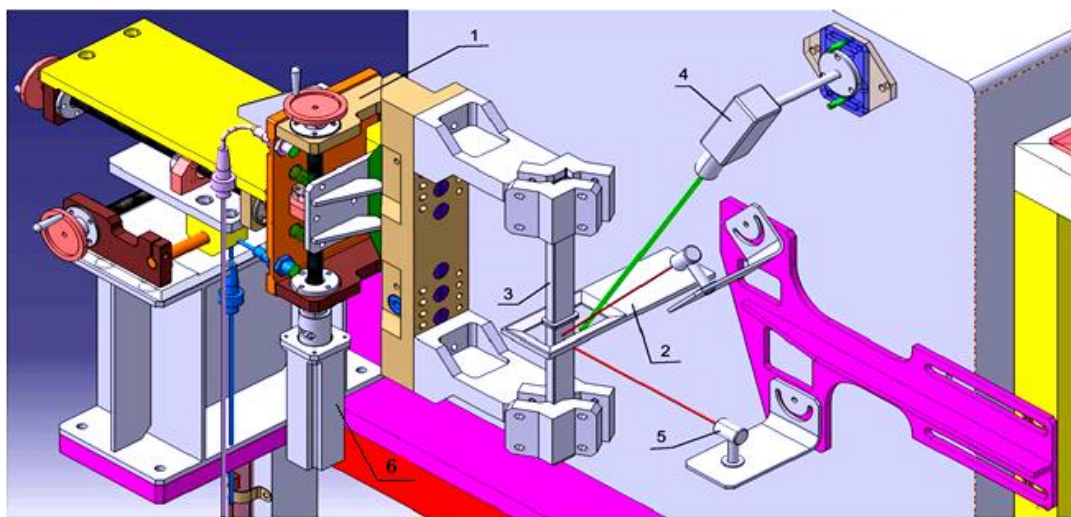

Figure 9. General view of the working area of induction heating facility: 1 – manipulator; 2 – inductor; 3 – waveguide; 4 – video camera; 5 – pyrometric sensor; 6 – electromechanical drive
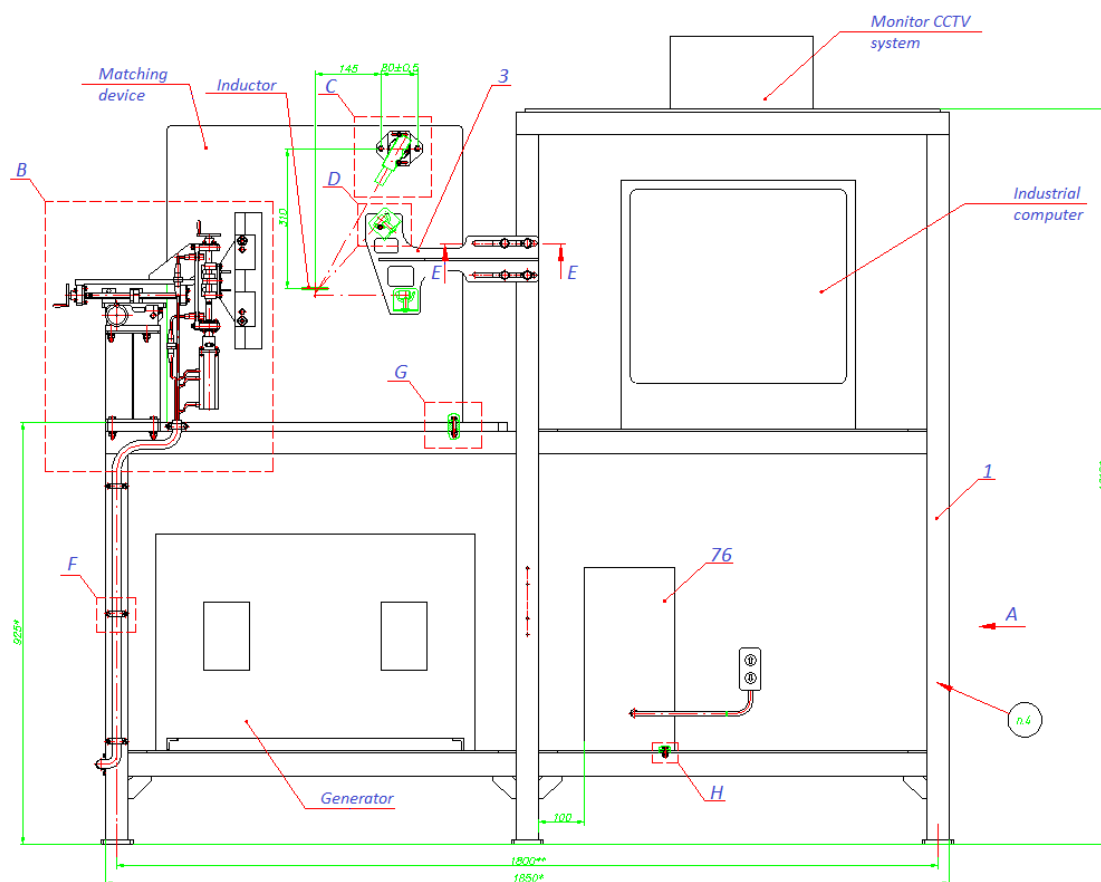
Figure 10. General view of the automated equipment complex for the waveguide tracts soldering

A scheme of equipment arrangement for the waveguide tracts induction soldering, which allows controlling the workpiece position relative to inductor freely, measuring the temperature in the heating area using two pyrometers and conducting video surveillance of the technological process, is shown on the above presented figures. Video surveillance allows staff to remotely control the technological process, thus completely eliminate influence of harmful factors on human health [11].

Conclusion

As a result, a set of automated assembly equipment for induction soldering AFD elements with pyrometric temperature control, which allows to manage the process of induction heating, to prevent overheating and destruction of the soldering products, to increase stability of the induction soldering process, to improve the quality of manufactured products, thereby to reduce the time and the material costs for the production, is developed. Developed automated equipment complex by remote control and monitoring of the soldering process, will reduce the impact of harmful production factors on personnel involved in soldering AFD elements.

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