Simulation of electromagnetic and thermal processes during induction heating of pipelines in Elcut 5.1

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Abstract. The article discusses the issues of modeling induction heating in the process of induction brazing of pipelines in a protective gas environment. Elcut 5.1 software product is used for modeling. The modeling of the following physical characteristics of the induction heating process is carried out: the electromagnetic field formed by the inductor, the distribution of eddy currents over the elements of the pipe being welded, the temperature distribution. On the basis of the developed simulation models, the influence of the position of the pipeline system assembly in the inductor window and the influence of the frequency of the current generated by the generator on the efficiency of the induction heating process are evaluated. The results obtained in the course of the study make it possible to efficiently adjust the technological parameters of the process of induction brazing of pipelines in protective environments and, accordingly, to improve the quality of the formed permanent joints.

1. Introduction

In terms of the number of permanent joints performed at mechanical engineering enterprises, brazing is in second place after welding, and in some industries, it has a leading position [1-3]. Soldering is widely used both in the manufacture of small batches of various products and in the performance of repair work, as well as in the production of structures under conditions of serial and mass production [4, 5]. According to experts, at present, soldering has taken a worthy place among the technologies for joining materials due to its unique capabilities, the main of which are a variety of heating methods and the ability to join dissimilar materials and composites that cannot be joined by other methods [6-8].

The main consumers of soldering technologies at present are the aviation and space industries, as well as enterprises producing refrigeration and cryogenic equipment, devices and electronic circuits, and heat exchange equipment [9, 10]. Soldered joints are distinguished by good appearance and high strength, both under static and dynamic loads [11, 12].

Within the framework of the presented article, the study of electrothermal processes occurring during induction heating of pipelines in protective media was carried out [13].

2. The use of Elcut 5.1 for solving simulation problem

The process of modeling an induction heating system consists of two joint tasks: electromagnetic and thermal. The results of these tasks are pictures of magnetic and thermal fields, distributions of current density and heat release, temperature graphs, current density.
The system was simulated in the program for engineering analysis and finite element modeling ELCUT 5.1 Professional [14].

ELCUT allows solving two-dimensional problems, so it is convenient to use an axisymmetric model as an object of modeling.

There are several main stages of building models in the ELCUT program. The solution to the field problem is reduced to several sequential steps [15]:

- selection of the type of the problem to be solved (alternating current field, non-stationary heat transfer, electrostatics, magnetostatics, etc.).
- choice of the problem class (flat or axisymmetric); An axisymmetric problem is selected if the modeled object is a body of revolution: cylindrical workpiece, pipe, solenoid, etc.).
- creation of a geometric model (drawing of an object).
- setting the properties of materials (electrical conductivity, magnetic permeability, thermal conductivity, etc.).
- assignment of loads (currents, heat dissipation power).
- setting boundary conditions (values of field potentials at the boundaries of the computational domain, values of temperatures at the boundaries, etc.).
- building a mesh of finite elements.
- the solution of the problem.
- processing of solution results (construction of color maps, graphs of changes in a variable along some contour, calculation of integral values, etc.).

To carry out modeling and obtain a solution to the thermal problem, it is necessary to solve 2 types of related multiphysics problems.

The first is to solve the eddy current problem, the type of the problem is the magnetic field of alternating currents, the class of the problem in our case is an axisymmetric problem, since the main object of modeling is the pipeline. Next, we set the current frequency of the induction heating process of our study \( f = 66 \) kHz, we choose the usual calculation. The unit of length is millimeters.

The next step in building a model is creating a geometric model. Figure 1 shows the simplified geometry of the pipeline, connector and inductor. For further processing of the results, including the construction of graphs of the electrothermal processes of the pipeline during induction heating in an argon atmosphere, it is convenient to outline the characteristic (control) points A, B, C, D and E.

![Figure 1. Geometry of the "Inductor-pipeline" model. 1 - inductor, 2 - pipe, 3 - connecting element (adapter) of the pipeline, 4 - boundary conditions of the calculation area.](image)

At the next stage of building the model, we will set the parameters of the modeling object and the initial data presented in the table 1.
Table 1. Initial data.

| Parameter                              | Environment                                      |
|----------------------------------------|--------------------------------------------------|
|                                        | trumpet (steel) | inductor (copper) | argon | adapter (steel) |
| Outside radius of the pipe, mm         | 5               | -                 | -     | 6.3             |
| Pipe wall thickness, mm                | 0.5             | -                 | -     | 0.65            |
| Relative magnetic permeability         | 200             | 1                 | 1     | 200             |
| Specific electrical conductivity, S/m  | 7 000 000       | 56 000 000        | -     | 7 000 000       |
| Thermal conductivity, W/(K*m)          | 50              | 401               | 0.0173-0.057 | 50          |
| Heat capacity, J/(K*kg)                | 462             | 385               | -     | 462             |
| Initial temperature, K                 | 293             | 293               | 293   | 293             |

After setting the parameters and setting the required loads for the induction heating process (current density), it is necessary to select the boundary conditions of the model. Figure 1 shows two types of borders. The boundary condition in the form of a half circle limits the area of calculation of the argon shielding gas environment. The bottom border in the form of a straight line must coincide with the line of the X-axis. After that, we build a grid of given elements and solve the problem.

3. Simulation of electromagnetic processes during induction heating

When solving the problem of the magnetic field of alternating currents, we obtain the following results: when a current flow in the inductor, an electromagnetic field arises around it, the lines of force of which act on the walls of the pipeline and the adapter (figure 2). This field induces eddy currents in the workpiece, with the help of which heat is released directly in the workpiece itself.

![Figure 2. Magnetic field lines and magnetic induction vector, [T].](image)

For calculations, we assume that the inductor is located as close as possible to the pipeline wall. Figure 3 shows the distribution of the current density in the pipeline. During the simulation, the supply current frequency was set equal to 66 kHz. The current in the pipe does not flow through the entire wall thickness, but only in the surface layer and mainly where the magnetic field induction is maximum.
Figure 3. Eddy current density pattern in the pipeline, $i_{\text{eddy}}$, [$10^8$ A/m$^2$].

Figure 4 shows the graphs of the distribution of the eddy current density along the thickness of the pipeline wall (figure 4, a) and along the wall thickness of the pipeline adapter (figure 4, b).

Figure 4. Eddy current distribution graph over thickness: a – pipeline wall thickness, b – pipeline adapter wall thickness.

Figure 5 shows graphs of the current density distribution along the length of the outer wall of the
pipeline (figure 5, a) and along the length of the outer wall of the pipeline adapter (figure 5, b).

![Eddy current distribution graph along the length of the outer wall of the pipeline adapter: a – length of the outer wall of the pipeline, b – length of the outer wall of the pipeline adapter.](image)

Figure 5. Eddy current distribution graph along the length of the outer wall of the pipeline adapter: a – length of the outer wall of the pipeline, b – length of the outer wall of the pipeline adapter.

4. Simulation of thermal processes with induction heating

Figure 6 shows the distribution of heat dissipation of the pipeline and the workpiece adapter.

Figure 7 shows the picture of the thermal field of the pipeline and the connecting element during induction heating. Heat generation in the pipeline is observed directly in the places where eddy currents flow. The maximum temperature of the thermal field is 1126.85°C.

Figure 7 shows that the zone of the most intense heating is located next to the inductor, and then - in decreasing order, that is, the farther from the inductor, the lower the heating. The connecting element of the pipeline always heats up primarily due to the peculiarities of the distribution of the heat flow, and through the walls of the outer wall of the pipeline itself is further heated, as well as the medium of protective gases such as, in our case, argon.

For the given characteristic points A, B, C, D and E (figure 1), we will build a contour for plotting the temperature of the product (figure 8) with induction heating.

Figure 9 shows a graph of changes in the heating temperature of the pipeline and adapter along the contour of characteristic points.

According to figure 9, it can be concluded that the maximum heating temperature is 1399K at point B located on the pipeline adapter.
Figure 6. Heat distribution pattern in the pipeline, \( Q \ [1 \times 10^8 \text{ W/m}^2] \).

Figure 7. Thermal field pattern during heating.

Figure 8. The contour of changing the temperature of induction heating of the workpiece.
Figure 9. Temperature distribution graph for induction heating of a pipeline.

5. Study of the influence of the position of the inductor on the efficiency of induction heating

Modeling an induction heating system reveals the effect of various parameters on heating efficiency.

The higher the frequency of the supply current, the more the eddy currents are displaced by the magnetic field formed by them into the thin surface layers of the workpiece. Accordingly, the eddy current density increases on the surface and the workpiece heats up. The rest of the layers are heated due to thermal conductivity.

The current in the inductor also significantly affects the heating process. The energy released in the pipeline is directly proportional to the current induced in it. Consequently, the released energy depends on the current in the inductor.

Also, the position of the inductor relative to the pipeline affects the heating efficiency.

Figures 10, 11 show the simulation results of induction heating at different positions of the inductor.

Figure 10. The picture of the thermal field when the position of the inductor changes upward relative to the workpiece: a – δ_=1 mm, b – δ_=3 mm.
When you change the position of the inductor relative to the workpiece: a – $\delta_r$ = -1 mm, b – $\delta_r$ = -3 mm, c – $\delta_r$ = 0 mm.

When you change the position of the inductor relative to the workpiece of the pipeline and the adapter upwards in figure 10, b, you can see a redistribution of the thermal field and greater heating of the pipeline itself, in contrast to the adapter, which confirms the data that the zone of the most intense heating is located near the inductor.

When you change the position of the inductor relative to the pipeline blank and the adapter down in figure 11, and you can see a decrease in the thermal field of the pipeline itself, in contrast to the adapter, the adapter retained the same concentration of the thermal field (figure 11, a). With a step of the transfer vector $\delta r$ = -3 mm (figure 11, b), a complete change in the distribution pattern of the thermal field is observed, the heating temperature does not correspond to normal indicators for the steel brazing process. The maximum temperature on the workpiece is 1031 K (757.850 °C), and for induction brazing of steel parts, the temperature must be 1374 K (1100.850 °C).

6. Study of the influence of current frequency on the efficiency of induction heating

During the study, it was found that the frequency of the current has a direct impact on the speed of heating the pipeline. With an increase in the operating frequency of the inductor, the heating rate increases. This effect is explained by the fact that with an increase in the frequency of the current, the depth of current penetration in the steel decreases and, accordingly, the current density on the surface of the pipeline increases, which leads to faster heating.

Figure 11. The picture of the thermal field when the position of the inductor changes downward relative to the workpiece: a – $\delta_r$ = -1 mm, b – $\delta_r$ = -3 mm, c – $\delta_r$ = 0 mm.

Figure 12 shows the results of simulating induction heating at various current frequencies from 20 kHz to 50 kHz.

Figure 12. The picture of the thermal field with a change in frequency at given temperature 1400 K: a – inductor operation at frequency 20 kHz, b – inductor operation at frequency 40 kHz, c – inductor operation at frequency 50 kHz.

It can be concluded that the frequency of the current has a direct effect on the speed of heating of the pipeline. With an increase in the operating frequency of the inductor, the heating rate increases. This effect is explained by the fact that with an increase in the frequency of the current, the depth of current penetration in the steel decreases and, accordingly, the current density on the surface of the pipeline increases, which leads to faster heating.
7. Conclusion
In the framework of this study, the simulation of induction heating in the process of induction brazing of pipelines in an argon protective gas environment was carried out. Elcut software version 5.1 was used as a modeling system. Simulation was carried out of both the electromagnetic field generated by the inductor, the distribution of eddy currents over the elements of the pipeline being brazed, and the temperature distribution.

Using the proposed simulation models, an assessment was made of the influence of the position of the pipeline system assembly in the inductor window, as well as the effect of the frequency of the current generated by the generator on the efficiency of the induction heating process.

The results obtained in the course of this study make it possible to efficiently adjust the technological parameters of the process of induction brazing of pipelines in protective environments and, accordingly, to improve the quality of the formed permanent joints.

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