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SIMULATION OF ELECTROMAGNETIC AND THERMAL FIELDS IN THE PROCESS OF INDUCTION HEATING ON SMALL SPECIMENS WITH THE PRESENCE OF WELDED JOINT OF HIGH-STRENGTH RAILWAY RAILS

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Selection of heating mode, which provides an optimal combination of technological parameters to obtain the necessary structural and phase transformations of welded butt of high-strength railway rails, which is subjected to heat treatment, is a complex process that requires carrying out a large number of experiments with a significant consumption of time, labor, power and financial resources. To solve this type of problem, it is rational to use methods of mathematical and physical modeling, which are based on the use of mathematical models, numerical calculation methods and experimental data of physical modeling in determining key parameters of heat treatment process. For this purpose, based on the theory of similarity, a mathematical model of the process of heat treatment of small specimens was proposed, taking into account the interrelated properties and physical phenomena with the original study. A simplified model of the specimen is considered, on which the optimal heating conditions are tested and the properties of the weld metal subjected to heat treatment are investigated, after which the transition to specifying the conditions of heat treatment of the real welded butt of high-strength railway rails is carried out. This approach makes it possible to significantly reduce the resources in determining the optimal conditions of heating products of high-strength carbon steels, including butt welded joints of railway rails. 13 Ref., 5 Figures.

Keywords: induction heating, heat treatment, weld of railway rails, mathematical modeling, physical modeling, small specimens

When laying a continuous railway track, high-strength rails are used made of new generation steels with an increased carbon content. The base metal and welded rail joints [1, 2] should provide high mechanical characteristics, which are predetermined by an increased axial load and speed of the rolling stock.

To remove residual stresses and normalize the metal of welded joint of rails, heat treatment (HT) is used [3].

One of the most efficient methods of heating during HT process is the method of induction heating using a high frequency (HF) current, which has a number of advantages over other methods. These are contactless heating, high energy density in a specific area of the object subjected to heating, achieving high temperatures, ability to control the temperature field of the object, ability to heat the object in different media, environmental safety of HT process [4]. In connection with the abovementioned, the further investigation and studying the features of phase transformations in welded rail joints after HT process are important [5, 6]. The process of performing induction HT of bodies of a complex shape, which include rails of high-carbon steel, is characterized by a large number of interdependent parameters. Selection of the heating mode, which provides the optimal coincidence of technological parameters to obtain the necessary structural and phase transformations of welded butt of the rail, which is subjected to HT, is a complex process that requires a large number of experiments with significant time, labor, energy and financial resources.

To solve this type of a problem, it is rational to use methods of mathematical and physical modeling, based on the use of mathematical models [6, 7], numerical calculation methods and experimental data of physical modeling in determining key parameters of HT process. For this purpose, based on the theory of similarity, a mathematical model of HT process was proposed, taking into account the interrelated properties and physical phenomena with the original — the real object of investigation. Thus, at first, a small and simplified model of the specimen was considered, on which the optimal heating conditions were tested and the properties of the weld metal were investigated, which was subjected to HT, and then the transition to specifying the conditions of HT of the real welded butt of railway rails are specified.

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In this paper, the principles of mathematical modeling of electromagnetic and thermal fields in the process of induction heating of small specimens in the form of solid round rods at the presence of a transverse weld are considered. Methods of mathematical and subsequent physical modeling should be closely related. The calculated parameters obtained at the stage of mathematical modeling should be the basis for physical modeling, where on small specimens with a weld a real HT process occurs.

After recalculation according to the theory of similarity of the optimal parameters obtained at the stage of physical modeling, a transition to the study of HT of the weld of the real butt and the selection of its heating conditions occurs. In this way the search for optimal conditions of HT of a weld of railway rails is simplified.

To determine the basic parameters of the physical model of the «inductor-product» system, the development of a mathematical model was performed, which reflects the process of HF induction heating of a specimen of high-carbon rail steel with simulation of the welded joint zone. This allows calculating the basic electrical parameters of the system, as well as obtaining the space-time distribution of the temperature field during the process of HT performance. To solve this type of problem, it is possible to use software packages based on the finite element method. The following main elements of the axisymmetric model (Figure 1) were determined:

• a solid rod of a cylindrical shape with a diameter of 8.5 mm and a length of 110.0 mm with the properties and factors inherent in high-carbon steel and with the simulation of the welded joint zone in its center;

• three-turn water cooling inductor with a current of 200 A and a frequency of 130 kHz;

• airspace, bounded by the inner surface of the sphere surrounding the studied system.

The induction heating process is described by a nonlinear interconnected system of Maxwell and Fourier equations, respectively, for the electromagnetic and thermal fields with the corresponding boundary conditions [8].

To obtain the solution of the electromagnetic problem, the system of Maxwell equations is presented in the following differential form:

$$\mathrm{rot}\boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}; \ \mathrm{rot}\boldsymbol{E} = \frac{\partial \boldsymbol{B}}{\partial t};$$
$$\mathrm{div}\boldsymbol{D} = p; \ \mathrm{div}\boldsymbol{B} = 0,$$

where $\boldsymbol{H}$, $\boldsymbol{E}$ are the vectors of magnetic and electric field strength; $\boldsymbol{D}$, $\boldsymbol{B}$ are the vectors of electrical and magnetic induction; $\boldsymbol{J}$ is the conduction current density vector; $\boldsymbol{J} = \sigma\boldsymbol{E}$ is the conductivity current density; ρ is the density of a foreign electric charge; σ is the specific conductivity of the substance.

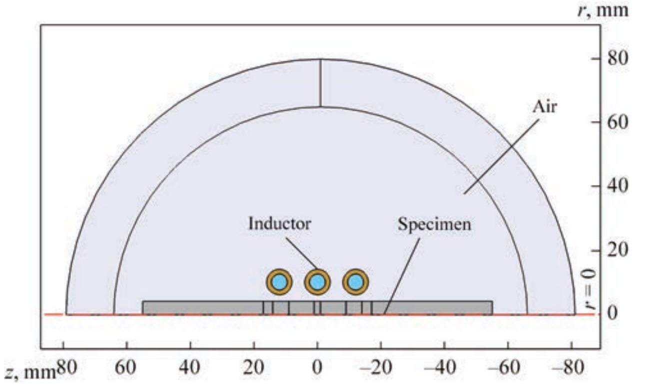

Figure 1. Axisymmetric model of induction system

These equations are supplemented by the equations of the relationship between magnetic field strength and magnetic induction, electric displacement and electric field strength, which characterize the electrical and magnetic properties of the medium:

$$B = \mu_0\mu_r\boldsymbol{H}; \ \boldsymbol{D} = \varepsilon_0\varepsilon_r\boldsymbol{E}.$$

where μ_0, μ_r are the absolute and relative magnetic permeability of the medium; ε_0, ε_r are the absolute and relative dielectric permeability of the substance.

With respect to the axisymmetric state, the mathematical model is presented in a two-dimensional cylindrical coordinate system $r0z$.

Since in the axisymmetric model the currents have a direction normal to the plane of the geometric model, than the vector magnetic potential A_φ has one component (0, <φ, 0), in contrast to the fields $\boldsymbol{H}$ and $\boldsymbol{B}$, which have two components (r, z) in this plane.

The mathematical model of the induction system is featured by the presence of the dependence of the electrophysical properties of materials on temperature.

To take into account the dependences of such physical parameters of steel as electrical resistivity $\rho_{st}(T)$, heat capacity $C_{p,st}(T)$ and thermal conductivity $\lambda_{st}(T)$ on the temperature T in the process of heating the specimen, they were set in the form of approximation functions based on data regarding high-carbon steels [9].

The nonlinear dependence of the magnetic permeability of steel on temperature and the loss of magnetic properties in the specimen under study when the temperature of the Curie point is exceeded, which changes the depth of magnetic field permeability into the steel, were also taken into account.

When modeling the induction heating process, as boundary conditions for the electromagnetic part of the model on the symmetry axis $0z$, the absence of the

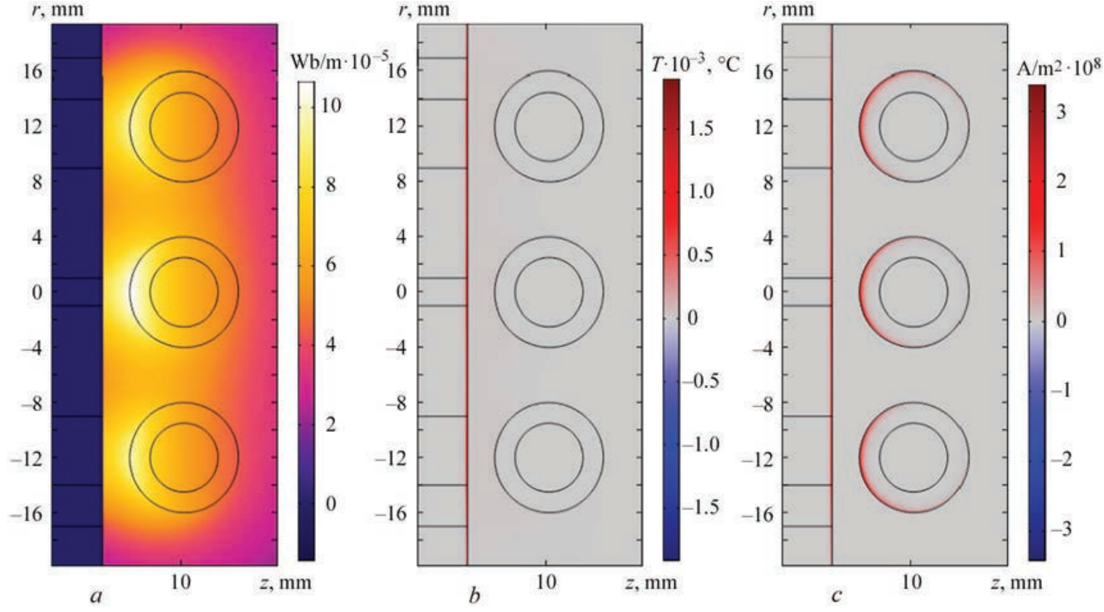

Figure 2. Distribution of magnetic potential A_φ (*a*); magnetic induction *B* (*b*); current density *J* (*c*)

tangential component of the magnetic field intensity and the presence of magnetic insulation at the boundary of the sphere were assumed (see Figure 1).

The mathematical model of the nonstationary thermal problem in the time domain includes the Fourier differential equation, which describes the distribution of the temperature field in the workpiece subjected to heating, in space and time:

$$P_{st} C_{pst} \frac{\partial T}{\partial r} - \nabla \lambda_{st} \nabla T = Q,$$

where *Q* is the specific power of the heat source.

To take into account heat losses in the mathematical model, the boundary conditions of the third kind in the form of heat exchange with the surrounding medium by convection and radiation from the surface of the specimen, which was subjected to heating, were set.

The condition of a constant temperature of 40 °C in the turns of the inductor in view of its cooling was accepted. On the axis of symmetry 0*z*, the Neumann boundary condition was accepted

$$\frac{\partial T}{\partial r} = 0.$$

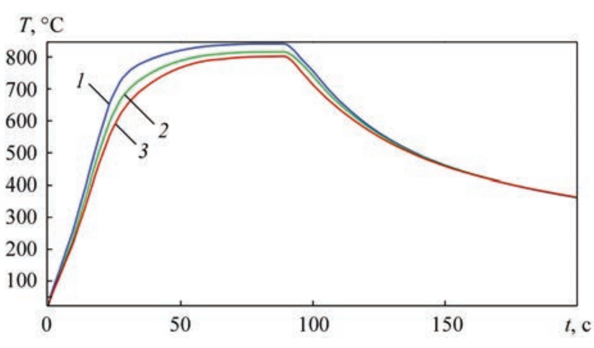

Figure 3. Change in temperature over time on the surface of the specimen along its length during heating: *1* — specimen center; *2* — 6 mm from the center; *3* — 11 mm from the center

As initial data, the amplitude value of current in the inductor and its frequency were taken. The calculation was performed in the following sequence:

electromagnetic — thermal calculation, taking into account the set density of a computational grid, properties of materials and boundary conditions.

During modeling the following physical processes were taken into account:

- current flow in the inductor taking into account the skin effect, ring effect and effect of proximity with the specimen;
- passage of the electromagnetic field and induction of eddy currents in the specimen taking into account the skin effect and effect of proximity to the inductor;
- heating of the specimen metal by eddy currents;
- losses of magnetic properties of the specimen metal after exceeding the temperature of the Curie point;
- thermal conductivity processes in the volume of the specimen metal;
- heat losses due to radiation and convective heat exchange.

In the process of solving the problem, the results concerning distribution of the magnetic potential A_φ (Figure 2, *a*), magnetic induction *B* (Figure 3, *b*) and current density *J* (Figure 3, *c*) were obtained.

According to the results of electromagnetic calculation, the influence of the skin effect, ring and surface effects in the inductor conductors is seen. The current is distributed nonuniformly along the cross-section of the conductors and it is concentrated on the surface of the inductor conductors, which are close to the specimen. A similar distribution is observed with the eddy current passing through the outer surface of the specimen under the inductor – along the perimeter of the specimen.

The purpose of thermal calculation is to determine the conditions of heating, providing a uniform distribution of thermal field on the surface of the specimen over time in the area, simulating the weld, to produce a homogeneous metal structure in the heating spot. In this case, the temperature should be higher than the phase transformation point A_{c3} and be in the range of 750–950 °C. A sufficiently uniform temperature distribution along the length of the specimen under the inductor (at a distance of up to 8 mm from the heating center) in the control points on the surface of the specimen was obtained (Figure 3).

Within 30 s from the start of heating an intensive growth in the temperature of the specimen occurs. During this period of time, the specimen has ferromagnetic properties, the depth of the skin layer is small and the density of the induced current in it is large, which provides a high level of heating power, which is generated in the specimen. After 30 s at the same values of current, the heating rate decreases due to a gradual loss of magnetic properties by the specimen metal and a decrease in the density of the induced current and, respectively, a reduction in thermal power, released in the specimen metal. As a result, the heating intensity decreases. After 50 and up to 90 s of the heating process, a forced temperature holding is carried out to normalize the metal of the weld and the near-weld zone (8–10 mm from the weld center) by regulating current in the inductor and specific power embedded in the specimen metal. After 90 s, the heating is stopped and the specimen is cooled naturally. Mathematical modeling of the induction heating process allows calculating and determining the required conditions of heating depending on configuration and geometric dimensions of the specimen and inductor at set thermophysical parameters of the specimen metal and energy parameter set to determine distribution of electromagnetic and thermal fields in the «inductor-product» system. After numerical calculation of heating conditions, the physical modeling of the process of heat treatment of welded joint of a small specimen is carried out in compliance with the conditions obtained by calculations and with their subsequent specification. Next, the hardness of the metal is investigated and the structural transformations formed in the metal are analyzed. If characteristics of the metal of the specimen, subjected to heat treatment, meet the necessary requirements, than having performed recalculation of the parameters of the heat treatment process according to the theory of similarity, it is necessary to proceed to studying the process of induction heating during heat treatment of the metal of the weld and near-weld zone of railway rails, at the same time maintaining the heating conditions obtained by the method of calculations and specifying them, and also correcting the inductor configuration [10–13].

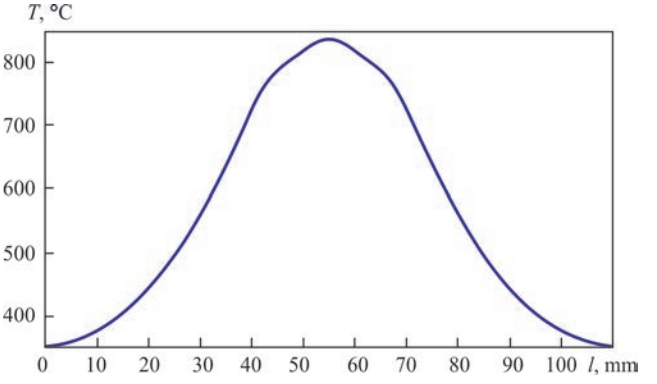

Figure 4. Temperature distribution on the surface of the specimen along its length at the end of heating process

Figure 4 shows the temperature distribution on the surface of the specimen along its length at the end of the heating process (90th second), and Figure 5 shows the temperature field distribution in the specimen (70th second) of the heating process.

Therefore, small specimens allow determining the optimal conditions of induction heating, which are initial when studying and selecting optimal conditions

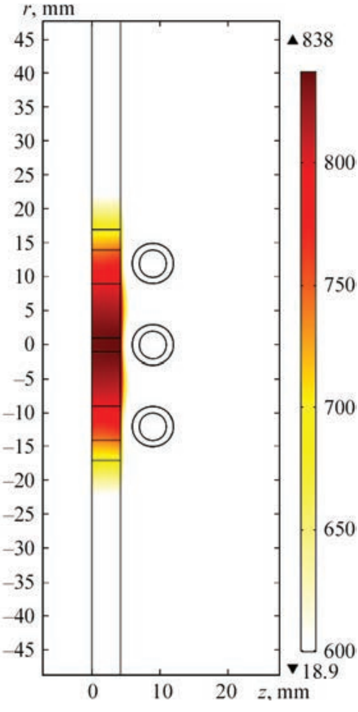

Figure 5. Temperature field distribution in the specimen

of induction heating to perform HT of welded butts of railway rails of high-strength steels.

Such an approach can significantly reduce the time, labor, energy and financial resources in determining the optimal conditions of heating high-strength carbon steel products, such as butt welds of railway rails.

Before performing physical heating of the weld of railway rails according to determined parameters of the heat treatment process, it is also rational to perform mathematical modeling of the process of heating the weld by the inductor that covers the weld and has a complex shape close to a complex cross-section of the railway rail itself. Performing mathematical modeling of the «inductor–measurement» system is possible in a three-dimensional 3D model using a computer of the required power, which is necessary to calculate the energy parameters of the inductor and its geometric dimensions. Performing mathematical modeling of the «inductor–measurement» system to calculate the energy parameters of the inductor and its geometric dimensions is the last and important stage of modeling, which is based on a large array of data and requires additional investigation.

Conclusions

1. The selection of heating conditions, which provides an optimal combination of technological parameters of the heat treatment process to obtain the necessary structural and phase transformations in the butt weld of high-strength railway rails is a complex process, that requires carrying out a large number of experiments, significant time, power, labor and financial costs. To solve this type of problem, it is more rational to use methods of mathematical and physical modeling, based on the use of mathematical models, numerical calculation methods and obtained experimental data of physical modeling in determining key parameters of the heat treatment process on small specimens with the subsequent transition according to the theory of similarity to determination of conditions of heat treatment of real welded butts of railway rails.

2. The use of small specimens allows selecting and determining optimal conditions of induction heating, which are the basis during further investigations and selection of optimal conditions of induction heating when performing heat treatment of real welded butts of railway rails of high-strength steels. Also, the use of mathematical models, numerical calculation methods and the obtained experimental data of physical modeling in determining key parameters of heat treatment process on small specimens allow determining energy parameters of the inductor and its geometric dimensions, as well as capacity of the power source and other induction equipment with a subsequent transition according to the theory of similarity.

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