Dynamic characteristics of numerical systems for induction surface heating

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Abstract. This paper describes the development, investigation and optimization of induction surface heating process of a workpiece taking into account its rotation by numerical simulation in a commercial package ANSYS® [1]. During the investigation it is necessary to select the optimal dynamic characteristics of the heating process in order to obtain the required temperature level and uniform temperature distribution on the surface of the workpiece.

1. Introduction
Induction heating is one of the most popular and effective methods of metal heat treatment. Preheating of metal workpieces is carried out before the next actions:

• quenching (cooling);
• rolling;
• forging;
• stamping;
• other plastic deformations.

Induction heating is superior to heat treatment in furnace or by open flame by many parameters. By the way of contactless energy transfer, it is possible to heat a selected area of the workpiece to the required depth during a short period of time. This method of heat treatment makes it possible to control the uniformity of the temperature distribution in the workpiece and to avoid oxidation and decarbonization of its surface.

The automated process of induction heating reduces time expenditure and energy cost for heat treatment of workpieces, increases the number of heated workpieces per unit of time and reduces their cost price.

The application of numerical simulation in the investigation and optimization of the high-frequency heating process allows to obtain enough amount of information for the development of induction installation and to reduce the time and material cost for these investigations.

2. Numerical simulation in a commercial package ANSYS®
Any material has electro- and thermophysical properties. These properties of the workpiece material positioned in an alternating magnetic field depend on intensity of magnetic field, the temperature of the workpiece and its heat exchange with the environment. It is the reason for the nonlinearity of the electromagnetic and thermal processes of induction heating, which can influence the temperature distribution in the workpiece.
Up to date numerical simulation in modern commercial packages is used to solve electromagnetic and thermal tasks of induction heating, which takes into account the nonlinear properties of the workpiece material. These packages are based on three numerical methods for solving differential equations: the finite element method (FEM), the boundary element method (BEM), and the finite difference method (FDM).

One of such package is the universal commercial package ANSYS®, based on the finite element method (FEM). It allows to find solutions of electromagnetic and electrothermal problems and to investigate various problems of mechanics and acoustics. Figure 1 shows an example of an algorithm for numerical simulation of the induction hardening process in a commercial package ANSYS®.

![Figure 1. The algorithm of the numerical model for induction hardening process simulation based on ANSYS® package.](image-url)
To begin with, the geometry of the induction system is developed: the geometry of the workpiece, the inductor and, if it is necessary, the magnetic core. An air space is simulated around it. Then the FEM mesh is generated in this model.

The next stage is the numerical simulation of the heating process, after which the process of the workpiece quenching is simulated [2].

The heating process includes electromagnetic and thermal tasks. Electromagnetic calculation allows determining the parameters of the magnetic field with the known specific electrical resistivity and magnetic permeability of each element of the workpiece, and also with the known initial temperature distribution in it. The result of the electromagnetic calculation is the distribution of Joule heat in the workpiece. On the basis of these results, the following thermal task will be solved.

At the end of the heat calculation, the final temperature distribution in the workpiece is formed at the next time step. If the result of the calculation does not satisfy the requirements, then the electromagnetic task is restarted, the initial conditions of which is the final temperature distribution in the workpiece after last thermal calculation. If the result of the calculation satisfies the conditions of the task, the resulting temperature distribution in the workpiece is the result of numerical simulation of the heating process.

After heating for next hardening, the workpiece is quenched in water, oil or air environment. To simulate the quenching process, only thermal calculation is used, where the initial temperature distribution in the workpiece is the result of the previous calculation of the heating process. The cooling conditions, which are indicated for the thermal calculation of the quenching process, take into account the temperature dependence of the heat-transfer coefficients [3].

The final result of the numerical simulation of the induction hardening process is the temperature distribution in the workpiece after the thermal calculation of the quenching process.

After the quenching process, a structural analysis of the quenched metal can be carried out. The structure of the hardened metal in the workpiece is estimated under the known main conditions of structural transformation, the austenitization temperature, the cooling rate, and the heating and cooling curves.

3. Numerical simulation of the induction heating process with change of dynamic characteristic

Figure 2 shows the induction system, which will demonstrate the numerical simulation of the induction heating process for the hot forming of the workpiece.

![Figure 2. The geometry of the investigated induction system.](image)
During heating of the metal some structural transformations and changes of its properties take place inside it. Most metals and alloys are well deformable after heating to high temperatures, because in the hot state the ductility of metals much increases. Before the hot forming process, the metal workpiece is heated to certain temperatures to impart the necessary properties to the metal, which allow deforming the workpiece without deteriorating the quality of the finished product.

The system under investigation consists of a workpiece and an inductor with a magnetic core and copper plates.

The workpiece is a steel hollow cylinder with a height of about 70 mm with a different wall thickness along its entire height. The maximum diameter of the workpiece is about 106 mm.

The inductor consists of four copper hollow line conductors with a cross-section of 10x15 and a wall thickness of 1 mm. The inductor is cooled from the inside by water. Each of the conductors is equipped with a U-shaped magnetic core, the height of which is 3 mm above and below the height of the zone subjected to heating. The top and bottom of each magnetic core are placed copper plates with an area that repeats the cross-section of the magnetic core. The inductor and the magnetic core are located along the workpiece at an angle of 60 degrees relative to each other.

This induction system should provide local heating of the steel workpiece (heating of the area having a bigger thickness) to the required depth up to a temperature of 840–850 °C for further hot forming of the workpiece. Also this system has to promote achievement of uniform temperature distribution on the set area due to rotation of workpiece in the inductor.

Numerical simulation facilitates the designing of induction systems for heating of rotating workpiece. Therefore, in the commercial package ANSYS®, numerical 3D models of electromagnetic and thermal processes in the induction heating system for the hot forming of workpiece were developed and investigated.

Due to the fact that the induction system is symmetrical about the YZ axis, all the investigations were carried out in the numerical 3D electrothermal model of the ½ part of the system depicted in figure 3.

Figure 3. 3D numerical model of ½ part of the system.

During the investigations for achievement of necessary value and uniform distribution of temperature in the workpiece before further mechanical treatment, values of a dynamic characteristic of inductor installation, such as current in the inductor were measured. One of the heat conditions is the difference between the maximum and minimum temperatures in the workpiece after heating, it has to be no more than 50°C. The big difference of temperatures in the workpiece can lead to emergence of cracks during process of hot forming.
During the first 38 seconds of heating the workpiece, the current in the inductor was 7 kA, during which time the surface layer of the workpiece was heated up to 944°C, the minimum temperature was 566°C. Then, with a smooth transition of 5.25 kA from 38th to 40th seconds, the current in the inductor was reduced to 3.5 kA. In this mode, the workpiece was heated from 40th to 82nd seconds, and at the end of the heating process the maximum temperature in the workpiece reached 887°C and the minimum temperature in the workpiece being 781°C.

At the 84th second the current was reduced to 1.75 kA, and then the next 5 seconds the current wasn't supplied in the inductor. Thus, the situation when the workpiece was moved from the induction heating installation to a hot forming installation was simulated. During this time, the temperature in the workpiece was leveled due to thermal conductivity, convection and radiation, and the difference between the maximum and minimum temperature values is 51°C, which satisfies one of the heating conditions.

Figures 4 and 5 show the final temperature distribution in the workpiece: the maximum temperature is 854°C and the minimum temperature is 803°C. The temperature distribution is practically uniformly along the outer diameter of the workpiece and its value reaches the required value.

![Figure 4](image-url) **Figure 4.** The finally temperature distribution along the outer diameter of the workpiece.

![Figure 5](image-url) **Figure 5.** The finally temperature distribution along the inside diameter of the workpiece.

The entire process of heating the workpiece with changes in the values of the power released in the workpiece, the current in the inductor, and the maximum and minimum temperatures in the workpiece can be seen from the diagram shown in figure 6.

The diagram shows that the power in the workpiece increases during 16 seconds and reaches a maximum value of 67 kW, and then it begins to fall. This is because steel is heated up to a Curie temperature of 835°C and loses its magnetic properties.

The temperature in the workpiece also increases very rapidly, until it reaches the Curie point. Then the temperature slowly increases. When the current of the inductor decreases, the temperature also falls slowly. The minimum temperature in the workpiece increases during the heating time, independently of the reduction in current and power. This is due to the heat transmission in the workpiece by thermal conductivity from the area with the maximum temperature to area with minimum temperature.
Figure 6. The diagram of the power released in the workpiece, the current in the inductor, and the maximum and minimum temperatures in the workpiece.

4. Conclusions
In the paper the use of numerical simulation for the development of the induction heating system of the workpiece with taking into account its rotation was demonstrated using the example of induction heating for hot forming. For this purpose, in the commercial ANSYS® package, numerical 3D electromagnetic and thermal models of this induction system were developed and investigation was performed with a change in the dynamic characteristics of the induction installation.

References
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