Numerical simulation of the induction heating process of a disk profile

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Abstract. This paper presents the developed parametric 3D model of disk heating. The numerical results reflect the change in the temperature profile of the heated pattern depending on the current value, current frequency, air gap size, workpiece thickness, workpiece diameter, heating time, number of inductor turns used and geometrical position elements of the systems “inductor - disk”. The results can be used for parametric studies and setting up the operation mode of installations for various sizes of disks.

1. Introduction

Environmental Most heat treatment technologies require uniform heating. The local heating will also call for a uniform temperature distribution, because this aspect determines the material properties homogeneity by volume and, as a result, the quality of the final product.

This study is dedicated to the process of disks heating. The disk is made by stamping and hardened with one beat, and the heating time is selected on the assumption of tempering a metal product. Heat treatment known as a tempering is widely represented in the industry.

2. Methods

The purpose of heat treatment is to provide local disk heating at the level of 450 °C with the minimum deviation of temperature from the set value. Initial data: the current value - 310 A, the current frequency – 2.5 kHz, the heating time - 30 s, the disk diameter -350 mm, the thickness - 3 mm and the design parameters of the inductor repeat the full-scale sample [1].

The skin depth depends on the steel grade, at a frequency of 2.5 kHz it is about 1.5 - 0.7 mm and magnetic permeability μ is in 10 - 40 range. It is known that to perform highly efficient tempering we at first have to heat deeper than the hardened depth. Volumetric heating with a small temperature difference along the cross section can be achieved thanks to the relatively low heating rate. The uniformity of temperature in a given area can be achieved both due to the high thermal conductivity, as well as due to the heating time control or power supply. The achievement of a given temperature level is possible with other current frequencies, but temperature distribution on the disk surface differs from the initial data.

During high-frequency hardening, tempering temperature has a significant effect on mechanical properties. The foundation for choosing the temperature level presented [1, 2], data are given after tempering, relatively through hardened disk sample with thickness measuring 3 mm. A moderate heating rate is able to ensure the temperature field stability, and as a result get high strength, ductility
and toughness. A further increase in tempering temperature will reduce the strength and increase the hardened disk toughness; therefore, overheating is impermissible.

It is important to take into account the heating concept. For flat metal disks heat treatment usually uses spiral and loop inductors or is done by transverse flux heating in combination with a magnetic core. We can apply rotation to achieve more uniform disk heating [3, 4].

Within this research, authors designed a 3D numerical model for simulation of the induction disk heating by using the ANSYS APDL, which includes a three-coil inductor and a hardened metal disk. Environment is air and it is described as a non-magnetic, non-conducting material, not containing electromagnetic field generation sources.

Thus, the heating time, the frequency and the power of the generator, the geometry and elements position of the system are described by parameters that can be easily corrected during the research due to the model parameterization [3 - 15]. Insofar as the system has rotational symmetry, instead of modeling the inductor complex geometry, it was decided to use a polar coordinate system, which has its own specifics in describing of the boundary conditions and loads setting. The initial modeling area is selected equal to $90^\circ$. The estimated time required to calculate for a given accuracy can be minimized. This is also made for the convenience and for the calculation accuracy improving. The finite element model of the system is shown in Figure 1. The mesh is concentrated in the heating area that provides flexibility and accuracy of the results in parametric studies.

![Figure 1. The finite-element 3D model of the system “Inductor - disk”.
The simulation area - $90^\circ$.](image)

These dependencies demonstrate the effect of one parameter on the temperature distribution pattern on the disk surface. There isn't specified below data, means that the original data apply to the system under research. To evaluate the proposed solutions and develop proposals for the optimization, it should to perform a parametric search for key system parameters. The solution of this problem is relevant in view of the desire to optimize production processes and minimize resource costs.

In Figure 2 shows a family of curves reflecting temperature profiles on the disk surface in various current frequencies.

![Figure 2. The dependence of the temperature profile on the disk surface at various current frequencies](image)

$f$: 1 - 500 Hz; 2 - 1000 Hz; 3 - 2500 Hz; 4 - 8000 Hz.
From the obtained result follow, the frequency of 8000 Hz is not recommended for use due to the pronounced skin effect, which results in significant overheating, and the 500 and 1000 Hz requires an increase in heating time or the current value. In Figure 3 shows, the effect of the current value influences at constant other system parameters.

Since the goal is to provide 450 °C the temperature level in the given area for specified time, the designed curves help to analyze and determine the range of operating current values (see Figure 3, Curve 3 and 4). In addition, it is established the operating mode setting affects to the maximum temperature levels, but not to the nature of the temperature distribution. Overheating is not allowed, because the result will be excessive mitigation in the case of tempering. The developed model also allows optimizing the heating time (see Figure 4).

![Figure 3](image-url) **Figure 3.** The dependence of the temperature profile on the disk surface at various current values I: 1 – 310 A; 2 – 350 A; 3 – 400 A.

![Figure 4](image-url) **Figure 4.** The dependence of the temperature profile on the disk surface at different heating time: 1 – 5 s; 2 – 20 s; 3 – 30 s.

In Figures 5 and 6 presents the results with inductor position variation relative to the heated disk.

![Figure 5](image-url) **Figure 5.** The dependence of the temperature profile on the disk surface at different inductor position variation relative to the heated disk. The distance from the first turn of the inductor to the disk center: 1 – 110 mm; 2 – 125 mm; 3 – 140 mm.
Figure 6. The dependence of the temperature profile on the disk surface at different air gap: 1 – 30.5 mm; 2 – 20 mm; 3 – 10 mm; 4 – 5 mm; 5 – 1.75 mm.

The designed dependencies allow us to estimate the influence degree of the edge effect and to use it for the regulation the supplied electrical energy. From plotted graphs (see Figure 5, 6), one can observe the trend of temperature changing due to an increase in the covered area of the disk by the inductor. Significant temperature difference in the heating zone is not observed. Curve 4 has the closest approximation to uniform heating in a given zone (see Figure 6). The choice of the air gap size also depends on the width of the heating zone and can be different for different sizes of disks. The results of the thickness influence and disk diameter are presented in Figure 7, 8.

Figure 7. The dependence of the temperature profile on the disk surface at different disk thickness: 1 – 1 mm; 2 – 3 mm; 3 – 5 mm; 4 – 7 mm.

Figure 8. The dependence of the temperature profile on the disk surface at different disk diameter: 1 – 350 mm; 2 – 380 mm; 3 – 400 mm; 4 – 420 mm.

From the results (see Figure 7, 8.) follows is necessary to heat disk-shaped products of various diameters and thicknesses, it requires to adjust the arrangement of the inductor turns or to considers...
the switching the magnetic core, which allow to adjust the width of the heating zone. The optimal results for a 350 mm disk with a thickness of 3 mm are shown in Figure 9 - 11.

![Figure 9. Joule heat distribution in the disk.](image)

![Figure 10. The final temperature distribution after completion of the heating process. The current value - 310 A.](image)

![Figure 11. The final temperature distribution after completion of the heating process.](image)

The above results were obtained using a three-turn inductor, which is satisfactory when a heated sample has diameters in range from 268 to 350 mm. For heating larger disks diameter should include a larger number of inductor turns. An example of the achieved target temperature level for a sample with a diameter of 420 mm is shown in Figure 12-14.

![Figure 12. Finite-element 3D model of the system “Inductor - disk”.](image)
The uniform temperature distribution was obtained in the specific zone in the range of the target temperature level as a result of parametric studies. These model are valid for heating disks of a complex profile by using spiral, loop inductors, transverse flux and longitudinal flux heating.

Based on the developed finite element model, the simulation of electrothermal processes during the induction heating of a simple disk profile was carried out. In view of the operating frequency and the inductor design, the through heating is simulated for tempering. This allowed to minimize the temperature gradient over the cross section in the disk heating zone. A numerical study did not take into account the presence of a hardened layer, in practice this would mean that the hardness be reduced unevenly, but in an optimal way.

3. Conclusions

Numerical results correlate with the experimental data. The problem-oriented program for numerical simulation and research of electrothermal processes successfully can be applied to optimal search for geometrical, positional, electrical configurations. The developed “inductor-disk” system also can be used for various heating problems (preheating), for compromise solutions searching in determining the suitability of heating concept.
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