Simulation of induction heating of a ferromagnetic plate with a covering inductor

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Abstract. The paper presents the features of numerical simulation of induction heating of a ferromagnetic plate by a covering inductor when powered from a voltage source, a method for calculating a symmetric system containing an odd number of turns is described. The calculation results are compared with experimental data. The influence of the correction of the magnetization curve on the correspondence of the simulation and experimental results is investigated.

1. Introduction
Numerical simulation of rectangular ferromagnetic plates induction heating by an enclosing inductor is quite complicated problem for numerical simulation. The geometry of the induction system requires the calculation of a three-dimensional model. Nonlinear B(H) dependence and temperature dependence of the magnetic properties require the use of special calculation methods and significantly increase the computational effort. This paper discusses the features of calculating a similar problem in two programs for numerical modeling: JMAG and Universal 3D.

2. Experiment description
The study was based on the results of experiment on a ferromagnetic plate induction heating. The material of plate is steel 45. The inductor has oval shape. It powered by a power source with a frequency of 8 kHz [1]. A sketch of the induction system is in Figure 1.

Fig. 1. Sketch of the inductor with the plate.
The inductor consists of 13 turns of a square copper tube 10 mm wide and 1 mm walls thickness. The height of the inductor is 170 mm. The heated piece is a plate 62 mm wide, 22 mm thick, 300 mm long, symmetrically located in the inductor. During 60 seconds of heating, the temperature of the plate was controlled at 4 points, the voltage and current of the inductor were also taken. As a result of the experiment, the workpiece was heated to a temperature of 865 °C at the hottest point.

3. Models of inductor

To create models of the inductor, two programs were chosen: a commercial numerical simulation package JMAG and a specialized program Universal 3D, developed for simulation of flat bodies induction heating. The choice of these programs was made because of their functionality, the possibility of three-dimensional electrothermal problem calculation with a nonlinear dependence of the magnetic permeability on temperature and magnetic field strength. JMAG uses the finite element method to calculate the electromagnetic and thermal problems [2]. Universal 3D calculates the transverse and longitudinal electromagnetic problems [3,4], thus reducing the number of measurements to two and significantly speeding up the calculation process.

The model in JMAG contains 1/8 of the entire induction system, since the inductor is symmetrical about three planes. To speed up the calculation, the turns of the inductor were simplified to the form of flat strips with a thickness of one penetration depth of current into copper (Figure 2). A "coils" (Fem-coil) and a resistor in the circuit were connected to each turn. The coil resistances were calculated using a “heavy” model with square coils and entered into the circuit connected to the finite element model.

![Fig. 2. Model of the inductor in JMAG with simplified turns.](image)

To get better agreement with an experiment, we decided to simulate a heating process in two modes: constant current (500 A) and constant voltage (120 V).

To simulate induction heating with constant power source current, it is necessary to connect turns resistances in series [5]. A resistance of the middle half-turns should be twice as large as full turn resistance, and current through the middle turn is two times lower. Turns resistances are presented in table 1.

| i  | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|----|----|----|----|----|----|----|----|
| Ri | μΩ |    |    |    |    |    |    |
| 1  | 137.2 | 107.9 | 109.5 | 120.0 | 17.0 | 116.2 | 117.0 |

The constant voltage mode requires more sophisticated circuit. An odd number of turns of the inductor requires correction of the middle turn resistance, cut along the plane of symmetry. This turn has half the cross-sectional area, therefore, physically, its resistance should be twice as large, but in this case, the voltage on the middle turn will be twice as much as on the rest, which will lead to an
incorrect calculation result. It would be wrong to "connect" a separate voltage source to the middle turn, since the voltage drop across the turns is uneven and changes when the part is heated. For the correct distribution of the electromagnetic field in the model, the current in this half of the turn must be equal to half of the current in the rest, and the voltage must be equal to the voltage on the whole turn. This can be achieved by connecting half of the integer resistance to the middle turn and setting the number of turns for the corresponding coil to 0.5.

The nonlinear magnetic properties of steel are described by two curves: the magnetization curve $B(H)$ (Figure 3) and the dependence of the magnetic susceptibility on temperature $\chi(T)$ (Figure 4). The magnetization curve was corrected for a more accurate calculation of the electromagnetic problem with nonlinear magnetic properties of the material. The dependences of resistivity, heat capacity, and thermal conductivity on temperature are taken from [6].

The inductor model in Universal 3D contains 1/4 of the inductor, since this program does not support creating coils with a non-integer number of turns. The magnetization curve, in contrast to JMAG, is corrected not by the amplitude, but by the effective value. This approach to adjusting the $B(H)$ curve is recommended in [7]. To determine the effect of $B(H)$ curve correction, JMAG calculations were made with and without correction.

![Graph of $\chi(T)$](image1.png)

![Graph of $B(H)$](image2.png)

**Fig. 3.** $B(H)$ curves for steel 45.

In both models, radiation losses from the surface of the part are taken into account. The emissivity of the plate surface is equal to 0.8.

**4. Constant current mode simulation results**

In this set of simulations inductor RMS current value was equal to 500 A. In the constant current mode a voltage value changes during the heating. In the Fig. 4 are the voltage-time curves of different simulations and experimental curve. The curve obtained by JMAG with the $B(H)$ correction is in much better agreement with the experiment than without it. Therefore, this calculation is considered the main one in this simulation.

The temperature distribution on the surface of the workpiece at the end of heating, obtained in JMAG is in Fig.5.

In the Fig. 6-8 is the comparison of temperature curves obtained from different simulations and the experiment. Up to the Curie point the temperature curves obtained in the JMAG program coincide with the experimental results. After the Curie temperature, the Universal 3D and JMAG results are similar, and the temperature value is lower than the experiment. The temperature drop in models may be caused by simplified radiation simulation without reflection from the coils.
When designing induction heating devices, special attention is paid to the efficiency, as well as the cos φ of the induction system: its value must be known to match the inductor with the generator. In Fig. 9 and Fig. 10 are shown the time dependence of cos(φ) and electrical efficiency, respectively.

Fig. 4. Voltage-time curves in constant current mode.

Fig. 5. Temperature distribution on the workpiece surface.

Fig. 6. Dependence of temperature on time. JMAG and Universal 3D.
Fig. 7. Dependence of temperature on time. Experiment and Universal 3D.

Fig. 8. Dependence of temperature on time. JMAG and Experiment.

Fig. 9. Dependence of power error on time. JMAG and Universal 3D.
Fig. 10. Dependence of efficiency on time. JMAG and Universal 3D.

Fig. 10 also shows the efficiency graph obtained as a result of simulation in Universal 3D with the resistances of the turns calculated analytically. It is noticeable that the efficiency value is lower than the one obtained using the resistances calculated according to the "heavy" model in JMAG. This is a good example of using specialized and universal software packages together to achieve the best result.

5. Constant voltage mode simulation results

Comparing the temperature curves, it can be seen that at all 4 points the experimental curves are higher than the calculated ones at the beginning of heating, but after passing through the Curie point, the calculated temperatures become higher than the experimental ones. This may be due to a drop in the voltage of the source after a decrease in the active resistance of the plate. The reason of this drop is in the loss of steel magnetic properties.

The radiation loss simulation in this set of simulations also does not take into account reflection from inductor turns. The real value of loss is lower than the simulated one. The difference insignificantly decreases due to convection loss, but at high temperatures convection loss is minor compared to radiation loss.

Figure 15 shows the graphs of the current through the inductor, obtained from the results of the experiment and simulations, in Figure 16 is the graph of the electrical efficiency of the inductor, in Figure 17 - the graph of $\cos \varphi$. The graphs of electrical parameters are made for models in JMAG with and without B(H) curve correction, in Universal 3D - with the resistance of turns calculated analytically [8] and taken from the calculation in JMAG.
Fig. 12. Temperature curves at point 2.

Fig. 13. Temperature curves at point 3.

Fig. 14. Temperature curves at point 4.
The cos φ graphs in all calculations are quite close to each other, the greatest deviation from the rest was shown by the graph from the calculation in Universal 3D with the coil resistances calculated analytically. The electrical efficiency plots differ more from each other, and again the result from Universal 3D with analytically calculated resistances is very different from the rest.

6. Simulation with transient electromagnetic case
The harmonic simulation of nonlinear electromagnetic case is fundamentally inaccurate. Even B(H) curve correction only decreases an error. The preference of harmonic simulation is relatively low computation effort. More accurate simulation type is transient electromagnetic simulation. The active
power in nonlinear electromagnetic case is a bit higher and closer to the experimental data, then the active power in harmonic case.

It was obtained that 512 steps per period in transient electromagnetic case is high enough to reach the power error (between circuit and FEM power) similar to harmonic simulation (Table 2).

**Table 2.** Power error in simulations with different number of transient steps.

| Number of steps per period | Power error, % |
|----------------------------|----------------|
| 32                         | 21.07          |
| 64                         | 12.49          |
| 128                        | 7.78           |
| 256                        | 5.25           |
| 512                        | 2.02           |

The power error of transient electromagnetic simulation becomes comparable to the harmonic one only with 512 steps per each period. To estimate the temperature difference, we simulated 10 seconds of heating using transient electromagnetic simulation with 512 steps per period. The computation time for such calculation was almost equal to 100 hours.

On the Fig. 17-20 are a comparison of harmonic, transient simulation and experimental data.
Temperature curves obtained using transient electromagnetic simulation is much closer to the experimental data in 1-st, 3-rd and 4-th points. The relative difference between temperatures in each point is over 10%. This difference can significantly influence on heated (or hardened) metal structure prediction accuracy. On the other side, the computational effort for the transient simulation with 512 steps per period was almost 4 times more than for the harmonic one. To decrease the simulation time in inductor designing process, we can use harmonic models for rough calculations and transient ones in the end, to get the most accurate result.

7. Tables
Based on comparison of the experimental data with the simulation results, the conclusion about the applicability of the investigated programs and calculation methods can be made. The best coincidence of the current value with the experimental results was shown by the commercial JMAG package with the corrected B (H) curve; the results in Universal 3D are significantly lower than the experimental ones. The temperature graphs in Universal 3D are closer to the experimental results, but they still show a significant increase in the heating rate after passing through the Curie point, which is not observed in the experimental curves. Experimental temperature graphs are in better agreement with the curves obtained in the simulation of the current loading mode. The reason for this may be the operating mode of the power supply used in the experiment. A significant advantage of Universal 3D over JMAG is its calculation speed. It took about 100 hours to simulate 60 seconds of heating in JMAG, while Universal 3D coped with the same mesh density in 80 minutes.

To obtain better agreement with experimental data, transient electromagnetic simulation can be used for “the last calculation”. More rough values of parameters can be relatively quickly obtained.
from harmonic calculation with B(H) correction. Using both methods consequently, the most accurate result can be reached for acceptable time.

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