Potential of open source simulation tools for induction heating

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Abstract
The paper describes simulation of induction heating process of ferromagnetic steel, when a full non-linear model is used: a temperature dependent B-H curve is taken into account. The full B(H,T) model is essential to obtain accurate results, which are confirmed by experimental validation. The paper also points out sensitivity of the model to slight variation of magnetic properties of material like Curie temperature, which might vary for steel of different grades. All results in the paper are obtained using open source simulation tools that demonstrates high accuracy compared to experimental results and benchmarked commercial software ANSYS Classic.

Keywords: induction heating, simulation, open source

Introduction
Numerical simulation procedure is mentioned frequently as a major factor for the successful design of complex induction heating and hardening coils [1]. While manufacturing of physical prototypes cost significant price in terms of materials, machining expenses, labor costs, engineering and, finally, time, practice shows that simulation might be an efficient way to shorten a design workflow down to a single iteration if numerical methods are used wisely prior to physical prototyping. This paper aims to examine necessity to implement a full non-linear magnetic model for induction heating of ferromagnetic materials like carbon steel. Such model simultaneously includes a B-H curve and its quantitative change with temperature raise. If taken into account, a sophisticated B(H,T) model may increase accuracy of numerical prediction of heating process, thus, adding value to a simulation software. However, such non-linear modelling cannot be performed analytically or using simple calculation sheets, FEM software is necessary.

Regarding FEM software, traditionally, only enterprise level companies could afford numerical simulation tools, since not only high costs of software itself, but also long learning period and the highest qualification of engineers needed in order to run simulations in time-efficient way. This paper has the aim to demonstrate that such times will likely pass away very soon! Open source tools, which are not only free, but also provide access to their source code, nowadays, are able to perform very accurate and time-efficient calculations. Since full access to the source code is provided, such software are very cooperative to slightly changes of models, including such enhancement as B(H,T) non-linearity.

Nevertheless, beside accuracy, the biggest concern for open source simulation software is the significant time needed in order to set a case in an open source tools. Since they usually provide low quality user experience and, frequently, have no user interface at all, open source tools require up to thousand additional hours per year if compared with user-friendly commercial software.

Because of all mentioned factor, only enterprise level companies with significant R&D departments are able to run simulations in time-efficient way and, therefore, are able to produce efficient coils for heating and hardening of complex parts. However, CENOS platform developed the unique technology, which is able to connect the best of various open source tools in simulation platform, which is simple in use and focused on induction heating.

The present paper will demonstrate simulation cases of induction heating of a billet, which are performed using GetDP open source software, coupled with pre-processing tool Salome and post-processing tool ParaView, powered in time- and cost-efficient way by CENOS platform. The results of the simulation are compared with experimental works 1) by Scurtu & Turewicz at Leibniz University of Hanover [2] and 2) Di Luozzo et al. at University of Buenos Aires [3].

Mathematical model
Magnetic vector potential A and electric scalar potential V formulation is used (AV-formulation):

$$\nabla \times \left(\nu \nabla \times \vec{A} \right) - \nabla(\nu \nabla \vec{A}) + \sigma \left(\frac{\partial \vec{A}}{\partial t} + \nabla V \right) = 0, \ in \ \Omega_1; \tag{1}$$

$$\nabla \times \left(\nu \nabla \times \vec{A} \right) - \nabla(\nu \nabla \vec{A}) = J_s, \ in \ \Omega_2; \tag{2}$$

$$-\nabla \left(\sigma \frac{\partial \vec{A}}{\partial t} + \sigma \nabla V \right) = 0, \ in \ \Omega_1 \tag{3}$$

Here, $\nu=1/\mu$ - reluctivity, μ - permeability, σ – electrical conductivity, J_s – source current density. Ω_1 stands for a electrically conducting eddy current domain (a workpiece to be heated), Ω_2 stands for a non-conducting domain (air) and a domain with a current source (a coil).

Temperature field is determined by solving the heat transfer equation:

$$\rho(T)c_p(T)\frac{\partial T}{\partial t} = \nabla(\lambda(T)\nabla T) + Q. \tag{4}$$

Here, ρ – density, c_p – specific heat capacity, λ – thermal conductivity, Q – Joule heat source. On the outer surface of the tube, both convective and radiation heat losses are set:

$$q = h(T - T_{amb}) + \sigma_B\varepsilon(T^4 - T_{amb}^4). \tag{5}$$

Here, σ_B – Stefan Boltzmann constant, h – heat transfer coefficient, ε – emissivity.

To account for nonlinear phenomena in time harmonic simulation, fictitious time independent material is introduced. Magnetic field intensity change over period is not sinusoidal in ferromagnetic material, but linearization approach finds effective B_{eff} that leads to same integral energy as it would be in transient simulation:

$$B_{eff}(H) = \frac{2}{H}\int_0^H B(H')dH'. \tag{6}$$

The mathematical model is solved with the Finite Element Method (FEM), coded in open source tool GetDP. For time-efficiency, CENOS platform was used to set material and numerical parameters of the model in graphic mode as well as to combine GetDP computational algorithms with pre-processing tool Salome and post-processing tool ParaView.

Validation cases

Validation of numerical models were performed using 3 different cases, each of the case stands for the respective experimental results (the references are provided):

- **Case 1.1 – linear model** for aluminum, ref. [2];
- **Case 1.2 – µ(T) model** for carbon steel, ref. [2];
- **Case 2.0 – B(H,T) model** for carbon steel, ref. [3].

In the Case 2.0, the full non-linear magnetic model is represented by magnetic permeability as a function of both magnetic field intensity and temperature – µ(H,T):

$$\mu(H, T) = \left(\frac{B(H)}{H} - \mu_0\right)\left(1 - \left(\frac{T}{T_C}\right)^\alpha\right) + \mu_0. \tag{7}$$

where T_C is the Curie temperature, α is characteristic exponent of permeability temperature dependence and μ_0 is vacuum magnetic permeability. In the Case 2.0, $\alpha = 6$; the Curie temperature $T_C = 735$ °C.

Case 1.1: linear model for aluminum

Case 1.1 represents the simple linear model for induction heating of the aluminum billet. Fig.3 demonstrates that the results, obtained using the open source software GetDP, perfectly match both results of benchmark simulation by ANSYS and the experimental results [2]. The results represents temperature in the middle of the billet, at the symmetry axis, over heating time.
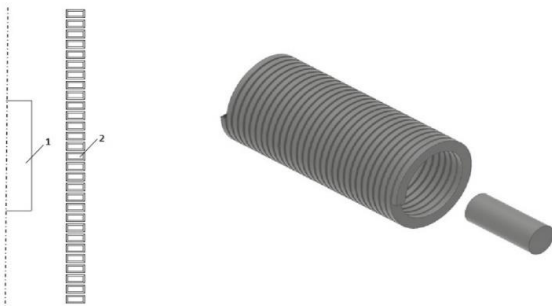

*Figure 1 – **Case 1.1 & 1.2**: 3D rendering of the parts (right) and the scheme of 2D axially symmetric system (left). On the scheme: 1 – the billet, 2 – the coil.*

*Figure 2 – **Case 2.0**: 3D rendering of the tube and the coil (right) and the scheme of 2D axially symmetric system (left). On the scheme: 1 – the tube, 2 – the coil.*

Case 1.2: µ(T) model for steel

It is obvious, that induction heating simulation of steel requires to consider non-linear properties of ferromagnetic materials. Frequently, simulation is limited to temperature dependence of magnetic properties µ(T) and does not take into account a B-H curve. Such approach is demonstrated also in [2], where experimental results of induction heating of a steel billet are obtained by Scurtu & Turewicz at Leibniz University of Hanover. Beside the experimental results, the authors published numerical results by ANSYS Classic, which is well-known accurate benchmark software (see Fig.4). While the simulation by Scurtu & Turewicz is performed taking into account only temperature-dependence of magnetic permeability µ(T), the simulated temperature perfectly matched the asymptotic (steady state) value, however, significantly

underestimates temperature during transient heating. E.g., at 10th second, the benchmark model of ANSYS predicts the surface temperature of the steel billet 100 °C less than measured during the experiment.

The simulation by open source tool GetDP coincides with the benchmark simulation, even more, slightly better predicts transient temperature during heating (see Fig. 4). The last fact is just because of adaptive time step, which allowed more accurately resolve the temperature raise. Nevertheless, the figure clearly demonstrates inability of the simple μ(T) model to predict temperature at the surface of the steel billet during the heating process.

Does a B-H curve help predicting the temperature accurately? While there is no exact information available neither regarding the grade of the steel used in the experiment, nor B-H properties of it, the calibration of analytical B-H model demonstrate improvement of simulation result on Fig. 4 (orange curve). However, one can recognize overestimated temperature after 10th second. Since B-H curve is calibrated and does not ground in material properties of the steel, we decided to double check necessity of the B(H,T) model in the Case 2.0, which provides accurate experimental data.

Table 1 – Case 1: Parameters of the validation cases

	Case 1.1	Case 1.2	Case 2.0
Geometric parameters			
Radius of the billet	30 mm		Inner: 16.5 mm/ Outer: 24.5
Length of the billet	150 mm		150 mm
Inner radius of the coil	70 mm		35 mm
Length of the coil	400 mm		50 mm
Number of windings	29		4
Operational parameters			
Current	1.3 kA	1.3 kA	725 A
Frequency	1.9 kHz	1.9 kHz	15 kHz
Material properties			
Material	aluminum	steel	
Thermal conductivity, Heat capacity, Electric conductivity	λ(T), c_p(T) , σ(T) [2]	λ(T), c_p(T) , σ(T) [3]	
Density	2.45 g/cm^3	7.87 g/cm^3	
Magnetic properties			
Over temperature	**constant μ = 1**	**μ(T)** [2]	**B(H,T)**, see Eq.(7)
B-H curve	-	**B(H,T)** [3]	**B(H,T)** [3]

Case 2.0: B(H,T) model validation

The Case 2.0 demonstrates accurate validation of B(H,T) model in respect to experimental data obtained by Di Luozzo et al. at the University of Buenos Aires [3]. The non-linear model is represented by Eq.(7).

Fig.5 presents the essential results, comparing temperature over time at the surface of the billet. Temperature maxima is located in the coil region and it falls rapidly outside of coil where no heating source is present. The curves represent the points at different distance from the plane or mirror-symmetry of the system, and demonstrate good match of simulation results with the accurate experiment.

Discussion of the results

In general, good agreement between numerical and experimental results is achieved. Main discrepancies are as follows:

- change in heating rate at the symmetry plane appears 2 seconds earlier in numerical results rather than according to the experimental data. Constant voltage regime was carried out at the experiment, while constant current regime is used in 2D simulation. So, while the current in the simulation model was constant during all simulation time, it was, obviously, increasing during the initial short time moment in the experiment;
- change in the heating rate at the symmetry plane appears at lower temperatures (ΔT≈15 K) in simulation results than in experimental results. We would like to argue here that the precise Curie point for the steel used is not known. Simulations at different Curie temperatures show that this change always appears slightly above (10-15 K) Curie point.

Change in heating rate appear at 747 °C, which is 10 degrees higher than Curie point. The same character is observed in simulations for variation of Curie temperature. Furthermore, increased heating rate appears immediately after Curie point for short period. This might be explained with electromagnetic effect of joined materials [5], which leads to local Joule heat maxima in non-magnetic part of steel above Curie point.
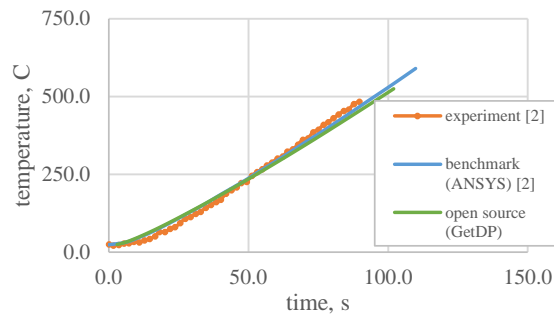
*Figure 3 – **Case 1.1**: Temperature at the middle of the aluminum billet over heating time. Experimental results and benchmark calculation ref. [2].*
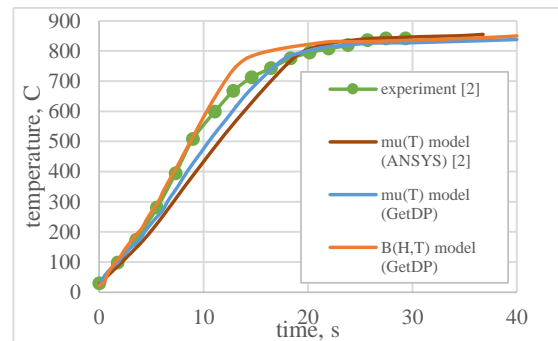

*Figure 4 – **Case 1.2**: Temperature at the surface of the steel billet over heating time. Experimental results and benchmark calculation of **μ(T)** and **B(H, T) model** [2].*
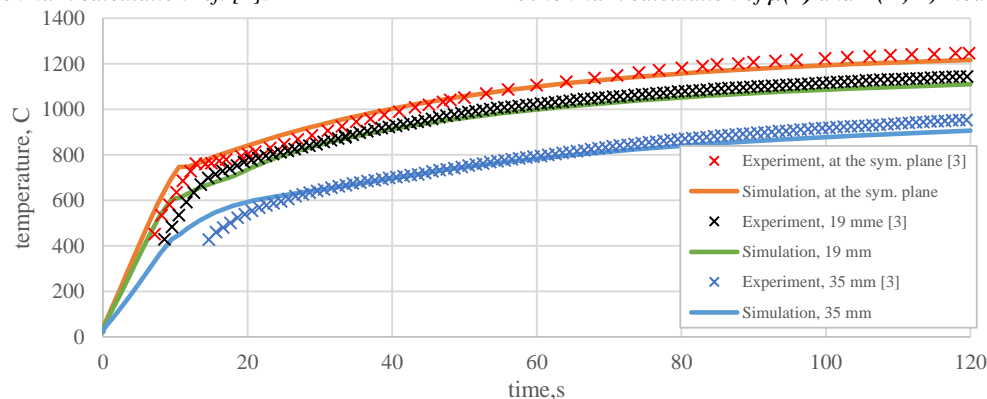

Figure 5 – Case 2.0: Simulation and experimental results (ref. [3]) of temperature at the surface of the workpiece. The curves are measured at different locations, the distance from the symmetry plane is specified in the legend.

Conclusions

Open source software GetDP has proven to be very reliable for modeling induction heating applications, especially due to its capability of capturing temperature dependent material properties and non-linear magnetic effects. Results obtained with GetDP are in good agreement both with ANSYS commercial software and experimental results.

Non-magnetic material heating has best agreement with experiment due to simpler mathematical model which leads to weaker coupling between thermal and electromagnetic problems.

Cases with ferromagnetic materials have good agreement but some details of heating curve are not captured. First reason for that are assumptions made, e.g. linearization of ferromagnetic material for time harmonic simulation. Second reason is insufficient knowledge of exact material properties, which turns out to be essential input data required for simulations. Even slight variation in Curie point had significant influence on temperature evolution

Cenos platform has proven its value for users of open source software as a great tool for simpler, faster and more efficient work.

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