Induction Heating Optimizing for Steel Billets: Advanced Electromagnetic -Thermal Modeling Approach

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Abstract

In the frame of the decarbonization of steel industry, with the aim of creating new technologies and applications, RINA-CSM developed for the EU project Horizon ModHEATech an electromagnetic-thermal model with Comsol Multiphysics in order to study the heating of a steel billet by induction, before rolling mills. The activity is related to the modeling of a multiphysics process controlled in power or voltage or current.

The model was used to determine the optimal process parameters in order to respect the production and quality requirements.

The thermal distribution and the current density distribution inside the billet has been studied on the basis of:

- Steel grades
- Applied supply power/current
- Frequency
- Initial/Final Temperature of the billet
- Productivity

The study has been focused on the Reheating Furnace of SIDENOR plant, as use case; based on the simulations results, different scenario has been compared to find the best layout configuration for introduction of induction heating in the industrial site.
Keywords: Electromagnetic/Induction Heating, Low-Frequency Electromagnetics, Heat Transfer, Energy

1. Introduction

The present work is aimed at simulating electromagnetic induction billet heating process by means of the development of a mathematical model and experimental investigation in the industrial field. An induction furnace (Figure 1) is made from a number of spaced inductors and the billet to be heated. The billet passes through an inductor with a certain speed, determined by the productivity.
The inductor is powered with the alternating current having a current intensity value I_{max} and a frequency value f_0. The alternating current of the inductor generates an electromagnetic field in the surrounding domain and this electromagnetic field generates induced currents on the surface of the billet. The induced eddy currents generate an increase in the surface temperature of the billet in the area under the inductor. The temperature tends to homogenize towards the center of the billet due to conduction in the areas external to the inductors.

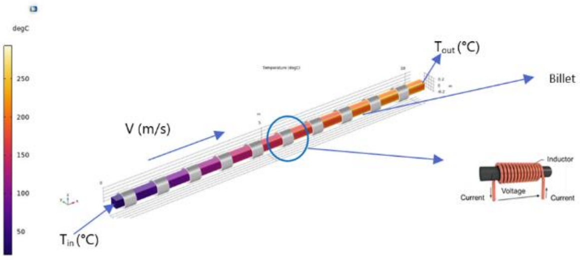

Figure 1. The Induction Furnace: thermal profile (left) and mechanical structure (right)

2. Theory

Induction heating is a process where electromagnetic physical and heat transfer phenomena are strongly coupled due to interrelated nature of physical properties. The magnetic field generated by the inductor (powered by alternating current) creates induced currents on the billet surface. Due to this physical effect, which is called **Skin Effect** [Figure 2], the spatial distribution of the current density inside the billet shows a maximum value at the surface of the workpiece and decreases inside the workpiece [1]. This current density distribution is quantitatively described by the electromagnetic penetration depth.

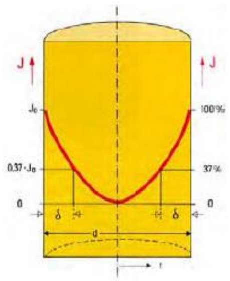

Figure 2. Skin Effect Laws [2]

The penetration depth of the billet induced current is described by the following formula:

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu_0 \mu_r}} \quad (1)$$

The penetration depth (δ) of induced currents is dependent on frequency f_0 and the property of material ($\mu = \mu_0 \cdot \mu_r$ is the magnetic permeability: μ_0 is vacuum permeability and μ_r is the relative permeability of the material- ρ is the electrical resistivity).
The eddy currents heat up the billets due to resistive losses in the material. The induction heating method is a direct heating process, because the heat sources are generated inside the workpiece itself and the heat is not transferred into the workpiece through the surface by heat conduction, convection or radiation. The induced currents heat the billet due to the Joule Effect. The **Joule Effect Laws** is described by the following formula:

$$P = RI^2 \quad (2)$$

where the terms of the equation are:

- P:it is the power that is transformed into thermal energy
- R: it is the electrical resistance of the billet
- I: it is the induced current intensity

The induced currents in a billet produce heat, and when the temperature rises, increases the electrical resistance (due to Ohm's second law the resistance increases). The Steel resistivity as a function of temperature is described by the following formula:

$$\rho = \rho_0 \cdot [1 + \alpha \cdot (T - T_0)] \quad (3)$$

where the terms of the equation are:

- ρ: it is the steel resistivity at temperature T
- ρ_0: it is the steel resistivity at the reference temperature (20°C)
- α: it is the thermal steel coefficient

The Ohm's second law is described by the following formula:

$$R = \rho \cdot \frac{L}{S} \quad (4)$$

where the terms of the equation are:

- R: it is the billet resistance
- ρ: it is steel resistivity
- L: it is billet length
- S: it is billet section

The magnetic permeability of billet steel also varies with temperature. It follows that the depth of penetration of the induced currents depends on the temperature. As the temperature increases, the penetration depth (δ) of the induced currents increases [Figure 3].

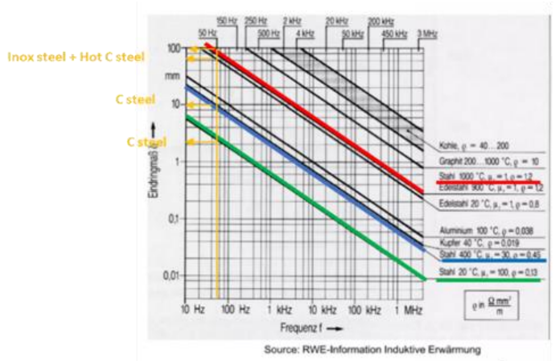

Figure 3. Skin Effect – Material – Frequency – Temperature [2]

The resistivity, the permeability and the penetration depth (therefore the penetration depth) depend not only on the frequency and temperature but also on the type of material. Stainless-steel billets and carbon-steel billets have a different property [Figure 6]. It has been estimated that at low temperatures (below the Curie temperature: *the Curie temperature is the temperature above which some materials lose their permanent magnetic properties*) the relative magnetic permeability [Figure 4], the resistivity [Figure 5] and the penetration depth [Figure 6] of stainless steel is significantly different from those of carbon steel.

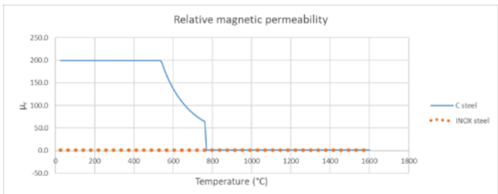

Figure 4. The magnetic permeability for Carbon Steel and Stainless Steel in function of Temperature

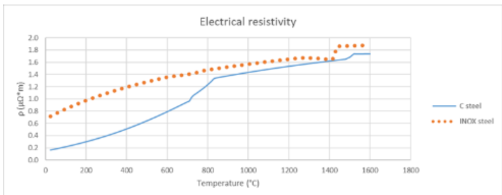

Figure 5. The electrical resistivity for Carbon Steel and Stainless Steel in function of Temperature

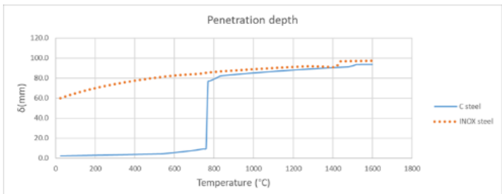

Figure 6. The penetration depth for Carbon Steel and Stainless Steel in function of Temperature

The magnetic and electrical properties of materials can be deduced from their chemical composition. A typical stainless steel is *316L* and a typical carbon steel is *C55E*. Both steels are a metallic alloy; stainless steel has a high presence of chromium (low in carbon steel). Chromium creates a passivated layer that protects the stainless steel from corrosion and creates a durable shine effect. Another element present in stainless steel is nickel, which improves its mechanical resistance. Carbon steel has a higher percentage of carbon than stainless steel; the high percentage of carbon allows the composition of the steel to be modified and subjected to heat treatments.

Stainless Steel

316L

C%	Cr%	Ni%	Mn%	Mo%	Si%	N%	P%	S%	Cu%
<=0,03	16,5-18,5	10-13	<=2	2-2,5	<=1	0,11	0,045	0,02	

Carbon Steel

C55E

C%	Cr%	Ni%	Mn%	Mo%	Si%	N%	P%	S%	Cu%
0,52-0,60	<=0,4	<=0,4	0,60-0,90	<=0,10	0,10-0,40		<=0,025	<=0,035	<=0,3

Table 1. Chemical composition for 316L (stainless steel) and C55E (carbon steel)

Solving the heat transfer problem simultaneously with the field propagation problem is therefore crucial for an accurate description of this process [3].

3. Experimental Set Up

The electromagnetic and thermal laws that regulate the electromagnetic induction heating process [4] have been confirmed by experimental laboratory tests [Figure 7].

Figure 7. Experimental investigation for the induction furnace

The thermal profile of the carbon steel billet, heated by induction by an inductor powered by an alternating current, was evaluated in the laboratory.
The tests were done as a function of time. The heating was carried out in a time linked to the distance traveled by the billet at the operating speed. The homogenization of the billet was emulated by not powering the inductor for a time equivalent to the distance traveled by the billet at the operating speed. Thermal profiles were measured with thermocouples. The thermocouple probes were placed in four fundamental points of the billet [Figure 8]:

- center: it is the heart of the billet
- middle: it is the average depth thickness of the billet
- surface: it is the billet surface (the central area)
- corner: it is the billet surface (the edge)

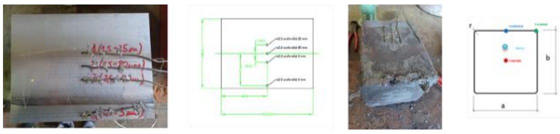

Figure 8 Experimental investigation for an induction furnace

The estimated temperature range varies from a minimum of 20°C to a maximum of around 1300°C [Figure 9]

Figure 9. Billet after induction heat treatment in the temperature range from 20°C to 1300°C

4. Model

A reliable, flexible and robust 3D model has been made for simulating the induction heating for steel billets in **COMSOL® Multiphysics** environment. The process is modelled as a Multiphysics system where electromagnetism and heat transfer are solved simultaneously to generate magnetic fields and temperature distribution. **The Electromagnetic Heating branch of the AC/DC module [**

Figure 10] is used. The Electromagnetic Heating branch includes Multiphysics interfaces that combine electromagnetics with heat transfer [5].

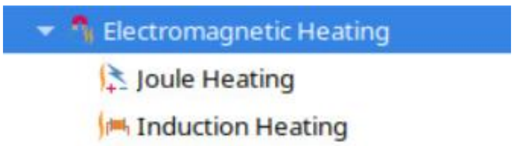

Figure 10 The Electromagnetic Heating branch of the AC/DC module

The model merges:

- the magnetic field generated by the coil that creates induced currents on the billet
- the heating by the joule effect generated by the currents induced on the surface of the billet
- the temperature gradients due to the skin effect
- the properties of the materials (once the billet temperature increases its electric, magnetic and thermal properties change, varying the values of induced currents and hence temperature gradients).

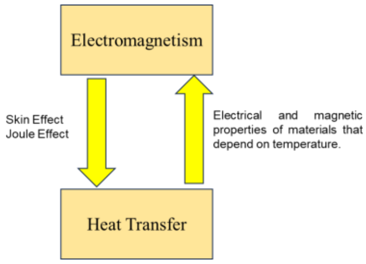

Figure 11. The electromagnetic combination with heat transfer [3]

The heating process of steel billets is described geometrically by a three-dimensional billet and by a number N of inductors equidistant from each other [Figure 12]. Each inductor (coil) is made up of n turns.

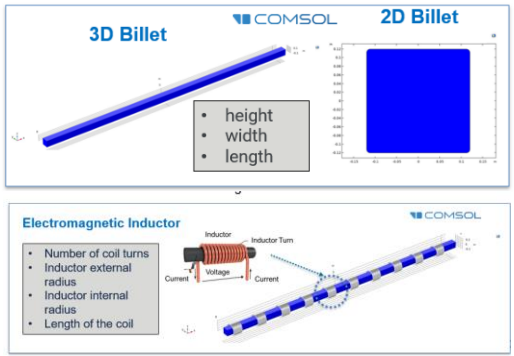

Figure 12 Geometric model of steel billet heating process

The physics of the **electromagnetic problem** is described by the following equations system:

$$\begin{cases} \nabla \times E = -j\omega\mu H & (5) \\ \nabla \times H = -j\omega\varepsilon E + \sigma E + J & (6) \end{cases}$$

the equations system is completed by the next set:

- $J = \dfrac{n * I_{coil}}{S}$ $\quad \forall$ coil=1, ..., N (7)
- $H_{in} = H_0$ (8)

<u>*where the equations*</u>:

- *in the system of Maxwell equations*, (5) is the Faraday's law and (6) is Ampère-Maxwell's law; E is the electric field, H is the magnetic field, μ is the magnetic permeability of the material ($\mu=\mu_0\cdot\mu_r$: μ_0 is vacuum permeability and μ_r is the relative permeability of the material), ε is the material dielectric constant ($\varepsilon=\varepsilon_0\cdot\varepsilon_r$: ε_0 is the dielectric constant in vacuum and ε_r is relative dielectric constant of the material) and $\omega = 2\pi f$ with $f = f_0$ exercise frequency.

- (7) J is the externally generated current density; I_{coil}, is the current that passes through the coil wire; N is the number of turns which are specified and S is the total cross section area of the coil domain
- (8) H_{in} is the initial magnetic field strength.

The physics of the **thermal problem** is described by the following equations system:

$$\begin{cases} \rho c_p \; \mathrm{u} \cdot \nabla T + \nabla \cdot q = Q + Q_e & (9) \\ \mathrm{q} = -k\nabla T & (10) \end{cases}$$

the equations system is completed by the next set:

- $Q_{conv} = h\,(T-T_{amb})$ (11)
- $Q_{rad} = \in \sigma_b\,(T^4-T_{amb}{}^4)$ (12)
- $u = u_{trans}$ (13)
- $T_{in}=T_0$ (14)

<u>where the equations:</u>
(9) represent the Fourier equation; ρ is the material density, Cp is the specific heat capacity, T is the absolute temperature, u_{trans} is the velocity vector of billet translational motion.
(10) represents the heat flux by conduction; k is thermal conductivity.
(11) the boundary condition is convection heat loss; h is the convection coefficient and T_{amb} is the ambient temperature.
(12) the boundary condition is radiation heat loss; e is the emissivity, sb is the Boltzmann constant and T_{amb} is the ambient temperature.
(13) represent the velocity vector of billet translational motion.
(14) T_{in} is the initial temperature.

The physics of the electromagnetic system and the physics of heat transfer are **coupled by the heat generated** by the induced currents. The heat generated is described by the following equation (the Joule Effect):

$$Q_e = \frac{J_e{}^2}{\sigma(T)} \quad (15)$$

where the terms of the equation are:

- Q_e: it is the heat generated by induced currents Je
- σ: it is the electrical conductivity of the material (σ=1/ρ–inverse of resistivity)

The set electromagnetic-thermal system is resolved in the geometric domain described above. In order to have an accurate calculation of the electromagnetic losses (since the penetration depth of the skin effect of the induced currents is less than half the side of the steel billet, a characteristic geometric quantity), the size of the mesh element is defined as a multiple of the skin depth. The mesh need only be sufficiently fine to resolve the geometry. Surface of steel billet and induction coil has dense meshing due to skin effect. Dense mesh was applied especially to the billet surface and between coils and billet, because of proper calculation of electro-magnetic phenomena. The study of the electromagnetic-thermal system is conducted in the frequency domain for an operating frequency $f = f_0$ (electromagnetic analysis is done in frequency domain and the translational motion-heat transfer analysis in stationary domain).

5. Simulation and Results

The obtained model allows to estimate, evaluate and verify the operating conditions of an industrial induction heating furnace for steel billets.
The model inputs are:

- the billet speed
- the billet geometry
- the billet steel (electrical and magnetic characteristics as a function of temperature)
- the number of inductors
- the geometric arrangement of the inductors
- the electrical power supplied by the inductors (the supply current, the frequency, number of windings and geometry of the inductors)
- the billet initial temperature

The model's goal is to attain the desired average temperatures after inductive heating with temperature gradients that are permissible along the billet profile. In post processing it is possible to evaluate:

- the billet current density distribution
- the billet temperature distribution
- the effect of frequency on the induced current density distribution of the billet
- the effect of frequency on the temperature gradients of the billet thermal profiles

- the geometric effect on the current density distribution
- the geometric effect on the temperature gradients of the billet thermal profiles
- the electrical power provided by the inductor necessary provide to the billet, in the form of thermal power, to obtain the eligible billet temperature gradients and maximum temperature regulated by the process.

Below is t reported the study on:

- the temperature distribution of a carbon steel billet heated in a 10-inductor magnetic induction furnace [Figure 13]. In this example, the initial temperature of the billet is 20°C and the operating frequency is 50Hz.

- the temperature distribution of a carbon steel billet heated in a 5-inductor magnetic induction furnace [Figure 14]. In this example, the initial temperature of the billet is 1050°C and the operating frequency is 3000Hz. For this type of induction heating, the Skin Effect of the current induced in the billet as the frequency varies is also studied.

In both cases, the inductors are appropriately spaced from each other to guarantee the homogenization phase of the billet in order to respect the temperature gradients along the profile of the billet. The thermal distributions of the simulations conducted suggest that the billet needs cooling to limit the thermal gradients to their permissible values it.

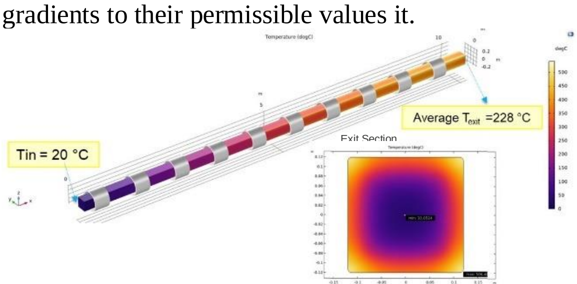

Figure 13. Carbon steel billet temperature distribution with T_{in}=20°C at f_0=50 Hz and 10-inductors

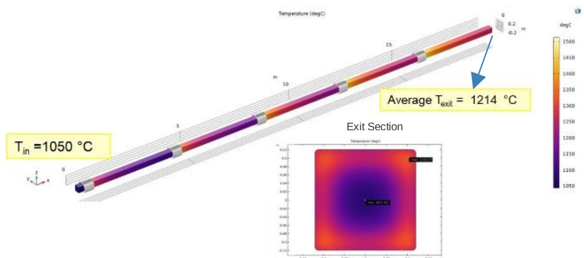

Figure 14. Carbon steel billet temperature distribution with T_{in}=1050°C at f_0=3000 Hz and 5-inductors

With the simulation of the billet 2D-profiles current density distribution, the Skin Effect of the induced currents [Figure 15] is studied as a function of the operating frequency [Figure 16]. The result is in agreement with the theory. Higher frequency improves the temperature distribution.

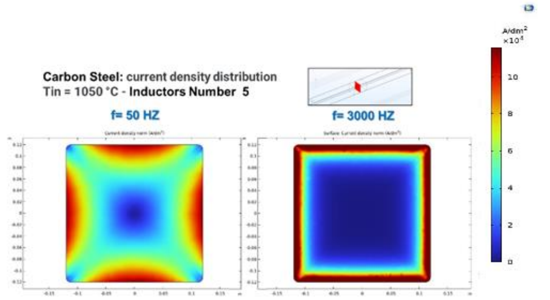

Figure 15. The billet 2D-profiles current density distribution as a function of the frequency (Skin Effect): cut plane yz.

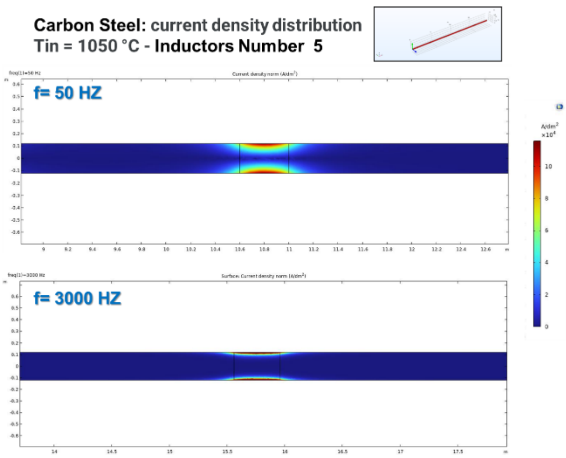

Figure 16. The billet 2D-profiles current density distribution as a function of the frequency (Skin Effect): cut plane xz.

Through the model, the temperature gradients inside the billet have been simulated and three temperatures have been compared to determine the quality requirements of the process [Figure 17].
There are three temperatures evaluated in the simulations:

- T-Surface
- T-Center
- T-Corner

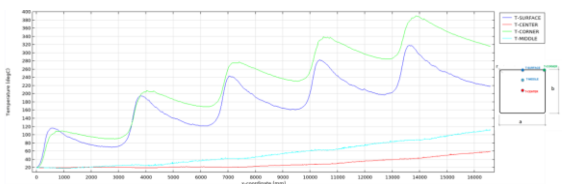

Figure 17. Carbon steel billet thermal profiles with T_{in}=20°C at f_0=50 Hz and 10-inductors

The numerical simulation was confirmed by experimental laboratory tests. Good agreement is found between the experimental results [Figure 18] and numerical simulation [Figure 19]. This validates the induction heating algorithm used for billet induction furnace.

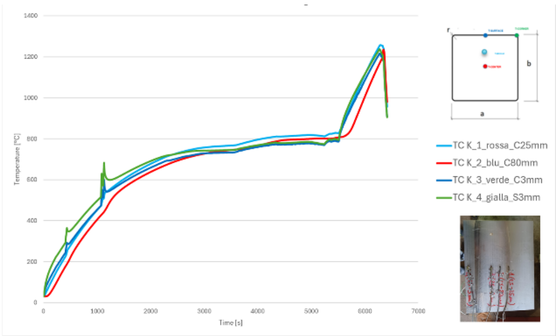

Figure 18. Billet thermal profiles for experimental laboratory tests.

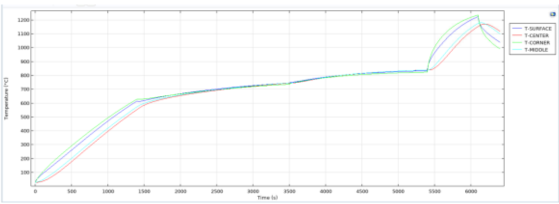

Figure 19. Billet thermal profiles in simulation with the same laboratory tests operating conditions

The results of the simulations were also verified on the data from the industrial field. Specifically, a study was conducted on the heating oven of the SIDENOR plant. After having calibrated the model, different scenarios have been compared to the SIDENOR system to find the best layout configuration for introduction of induction heating in the industrial site, based on the simulations results.

6. Conclusions

The model is a valuable tool for conducting feasibility study, analysis, design, testing, and maintenance of the electromagnetic induction heating plant. The model's results were validated by comparing them to real process data.
It has been proven that in simulation, it is possible to keep the maximum temperature difference in line with the requirements for product quality.
In the simulated cases, the impact of frequency was assessed. At low temperatures (below the Curie temperature), working at frequencies of the order of tens of Hz (for example, at 50 Hz) is the recommended method for the materials being studied; at high temperatures (above the Curie temperature), working at frequencies of the order of kHz (for example, at 3000 Hz) is the recommended method for the materials being studied.
By simulating the SIDENOR plant cases, it was possible to understand the importance of the homogenization phase of the electromagnetic heating furnace configuration. To obtain permissible temperature gradients along the billet profile, the space between two inductors (homogenization zone) must be appropriately sized. This dimension is related to the type of material, the geometry of the billet, the speed of the billet, the initial temperature of the billet, the thermal power provided by the inductors in the heating zone, and the operating frequency.
Different industrial plants will be simulated in the future, considering billets with different geometry, billets of different materials.
The system will be upgraded with additional physics (e.g. the insulation of the homogenization area to have less heat dispersion, i.e. less energy waste), as well.
The system can be optimized by reducing temperature gradients by regulating of:

- the electrical power of the inductors placed in series as a function of the billet inlet temperature at each inductor
- the frequency of each inductor.

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7. Acknowledgements

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