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Modular hybrid technology in steel plant production

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The steel industry is a cornerstone of the European economy, contributing 6.7% of global crude steel production (126.3 Mt in 2023). However, it is also a major source of greenhouse gas emissions, accounting for 4% of total EU emissions and 23% of those from manufacturing industries. Achieving carbon neutrality in this high-energy-intensity sector requires innovative solutions to reduce dependency on fossil fuels. The MODIPLANT project addresses this challenge by proposing renewable energy source (RES) based electrification of key downstream steel production processes. Specifically, the project focuses on decarbonizing reheating processes while maintaining high product quality, productivity, and economic viability. Two advanced technologies are being developed and tested. RES induction heating: a hybrid heating system will replace natural gas burners in hot dip galvanizing lines for steel coils at Marcegaglia's industrial plant. A novel electrical heating system for billets will be prototyped at Feralpi Siderurgica. Both technologies are supported by comprehensive metallurgical studies to ensure product quality is maintained or improved. These studies encompassed tests performed on a magnetic induction pilot line, conduction heating pilot line, and Gleeble simulations. Advanced simulations were conducted to model heating processes and predict metallurgical outcomes, and these were validated through experimental tests.

KEYWORDS: DECARBONIZATION; HYBRID HEATING; INDUCTION HEATING; ELECTRICAL HEATING; STEELMAKING; HOT DIP GALVANIZING; MICROSTRUCTURE; SIMULATION.

INTRODUCTION

European steelmaking transition to carbon-lean, "green" steel requires a fundamental change in the way steel is made, because our current processes are already at the technical and thermodynamic limits. The breakthrough technologies that the industry needs mean using hydrogen and renewable electricity to produce steel; they also mean capturing and either storing or using carbon that is emitted to bring the environmental footprint of our production as close to zero as possible [1]. In this scenario, to achieve emission reduction, a market for green steel production must be established. As also reported in the update of the New Industrial Strategy for Europe, the important role of industry in the transformation towards a carbon-neutral economy is recognized [2]. Steel production is related to a high impact in terms of resource exploitation and CO_2 emissions. This is considered a high energy intensity sector. Most of the energy demand in the steel sector is mainly based on fossil fuel, so finding and

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setting new ways to overcome the environmental impact of steel production is fundamental. The challenge is to cut emissions from energy-intensive industries. Modifying and enhancing current processes represents the most effective strategy to reduce reliance on traditional energy sources and to advance existing methodologies [3].
Once steel is produced and cast, it undergoes other operations, such as rolling, annealing, heat treatment, pickling, and others. Most of these operations require that the steel is treated at high temperature (900-1200 °C), with relevant demand of energy for heating. Most of this energy is still provided by fossil fuels, in particular natural gas. Table 1 shows estimated specific energy consumption and specific CO_2 emissions per tonne of product of the current pathways for iron and steel production in Europe, related to bloom, slab, billet mill and hot dip metal coating line. Considering the downstream steel processes, electrification represents a valid option.
The mitigation of the carbon footprint associated with traditional CH_4 burner systems can be affected by replacing them with hybrid heating systems that use both electrical and gas heating, optimally fueled by Renewable Energy Source (RES).

Tab.1 - Estimated specific energy consumption and specific CO_2 emissions per tonne of product [4].

	Primary Energy (GJ/t)	Direct Energy (GJ/t)	Total CO_2 emissions (tCO_2/t)	Direct CO_2 emission (tCO_2/t)
Bloom, slab and billet mill	2.501	1.783	0.125	0.088
Hot dip metal coating	2.108	1.491	0.104	0.059

The primary aim of the project is to offset thermal processes induced by decarbonizing them with innovative inductive and conductive heating systems. Induction and conduction heating focus on two critical applications, which are: the Hot Dip Galvanizing (HDG) process and billet reheating prior to rolling. The adaptation of the newly introduced technologies in the existing industrial lines needs to be considered and studied. Many factors, such as the compatibility between the old and new-line modules, heating treatment practices, and new technology efficiency and effectiveness, need to be deeply analyzed.
Specifically, the project focuses on decarbonizing reheating processes while maintaining high product quality, productivity, and economic viability. Two advanced technologies are being developed and tested: (a) RES induction heating: a hybrid heating system will replace natural gas burners in hot dip galvanizing lines for steel coils at Marcegaglia's industrial plant; (b) a novel electrical heating system for billets will be prototyped at Feralpi Siderurgica. Both technologies are supported by comprehensive metallurgical studies to ensure product quality is maintained or improved. These studies included tests carried out on a magnetic induction heating pilot line, a conduction heating pilot line, and through Gleeble simulations. Advanced numerical simulations were also carried out to model the heating processes and predict metallurgical outcomes. These predictions were subsequently validated through experimental testing.

METHODOLOGY

Metallurgical studies are conducted to ensure that product quality is maintained or improved. The methodology involves laboratory-scale testing and modeling to characterize the heating behavior and microstructural effects of fast heating on both flat and long products. In addition, industrial-scale feasibility studies were conducted to assess the technical integration, operational limits, and cost-performance trade-offs of the innovative hybrid heating technologies.

Laboratory experiments

The experimental activities at laboratory scale began with the collection of process windows from industrial partners, aimed at identifying the target temperatures and heating profiles required for different steel grades and product geometries. Metallurgical studies on flat and long products were carried out to observe microstructural evolution in accurately defined steel alloy specimens. Three alloys for flat products and one alloy for long products were studied, respectively: one structural steel (S), one dual phase (DP) and one interstitial free (IF) grade and one low carbon steel grade alloy for billets (see chemical compositions in table 2).

Preliminary experimental trials on flat samples, delivered in a cold-rolled state, were carried out to explore new process parameters for heat treatment, specifically high heating rates and temperature ranges. These trials also served to configure the heating system for subsequent experiments. Figure 1 below illustrates the initial pilot line setup used for these preliminary tests. The setup consists of a central induction heating (IH) system (max. power of 100 kW), surrounded by a sample handling structure, enabling induction-based heat treatments on steel sheet samples.

Tab.2 - Steel grades chemical compositions.

Material	Product shape	C	Mn	Si	P	S	N
S	Flat	0.14	0.63	0.01	0.01	0.02	0.02
DP	Flat	0.11	1.50	0.30	0.02	-	0.01
IF	Flat	0.0035	0.094	0.001	0.01	0.01	0.004
C	Long	0.20	0.80	0.23	0.05	0.05	0.012

Fig.1 - Experimental pilot line: first setup.

Tests were selected aiming at reaching the related target temperatures with high Heating Rates (HR) (see table 3).

Tab.3 Target temperatures and heating rates.

Material	Target Temperature range [°C]	Heating Rate [°C/s]
S	700-780	150÷200
DP	780-820	150÷200
IF	750-850	150÷200

The experimental trials have been performed at high power (between 50 and 65 kW) and at different handling system (line speed) velocities (between 1 m/min and 1.8 m/min). Cycles with high heating rates followed by immediate air cooling have been performed. The measured temperatures (using K-thermocouples) in the different samples ranged from 593°C to 1048°C. The heating rates for the samples tested ranged from 180°C/s to over 200°C/s. Metallurgical studies on flat products were conducted in parallel with the other experimental activities. In fact, continuous annealing cycles were simulated with a dilatometer (DIL 805 A/D/T) and a Gleeble thermomechanical simulator (Gleeble 3800). These microstructural changes were measurable and were modeled as well. The sample in the Gleeble simulator is heated using resistance heating. In the experiments performed, isothermal tests with varying holding time (between 0s and 30s), studies on heating rate (40°C/s, 80°C/s and 120°C/s), and investigations aimed at understanding the effects of processing parameters were conducted for the three steel grades. The thermal cycles of continuous annealing were modeled using a two-level factorial design approach for DP and S steel grades. For IF, the recrystallization behavior during annealing was modeled to describe the evolution of recrystallized fraction as a function of time and temperature. The main process parameters have been identified considering the characteristic thermal cycles of the steel grades in HDG line (see DP one in figure 2). Heating rates, soaking time and temperature, cooling rate and galvanization time and temperature were considered in the study. Microstructure evolution and mechanical properties of the steel alloys subjected to HDG process simulation were then analyzed.

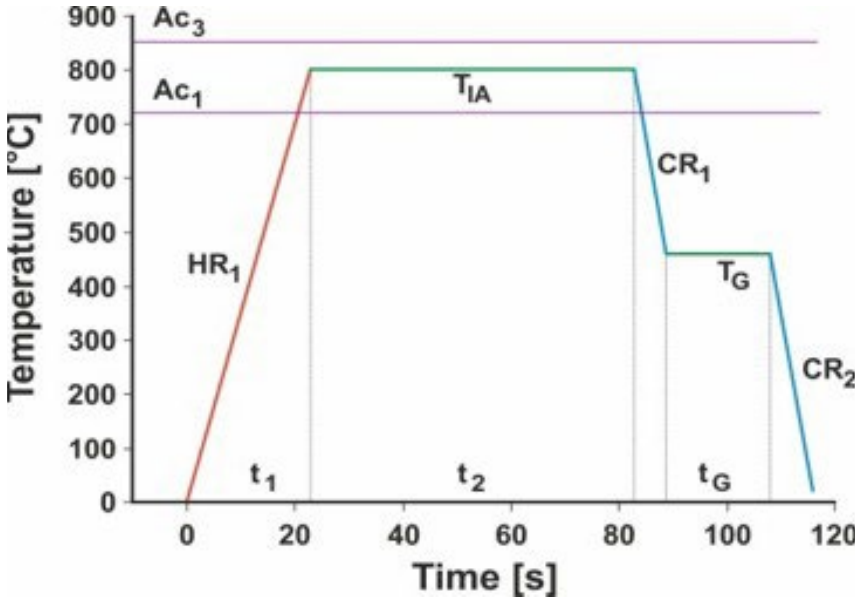

Fig.2 - Definition of the process parameters for the physical simulation of HDG process of DP steel.

Three holding temperatures with varying holding times were applied. Since recrystallization can start during the heating process, the strategies to heat the samples to the targeted temperature at the fastest rates were considered. The samples after the physical simulation experiments were investigated by a high-resolution scanning electron microscope equipped with an EBSD detector. A standard investigation was performed for the identification of the microstructure of S and DP steel samples subject to annealing simulations. For the samples of IF steel, a microstructural and textural investigation by EBSD was performed.

Billets of typical industrial dimensions, composed of low-alloy steel (C ≈ 0.20 wt.%), were used to analyze the inductive heating (IH) systems of the pilot rolling mill and in a vacuum induction furnace. The frequency and power of the furnaces were varied for this purpose and power, voltage as well as current needed were measured. Thermocouples inserted through dedicated holes measure the heating distribution in the cross section due to in-

duction and show its dependence on induction power, frequency and time. For the conductive heating experiments, heating treatments were performed at samples of different sizes to investigate the transformation phase behaviour, grain growth and grain coarsening as well as the dissolution of precipitates such as carbides and this the homogenization of the austenite. Conductive heating tests on the same steel grades for billet were performed on two experimental setups. First, cylindrical steel samples (Ø10 mm and Ø25 mm) were heated up in the MCU unit from Gleeble (see setup details in figure 3) to 1200°C at 10 and 30 K/s and held at peak temperature for 60s, then cooled in air. Second, square-section (10x10 mm to 20x20 mm, 200 mm length) steel samples were heated to 500 °C and 1100 °C in a retrofitted welding simulator.

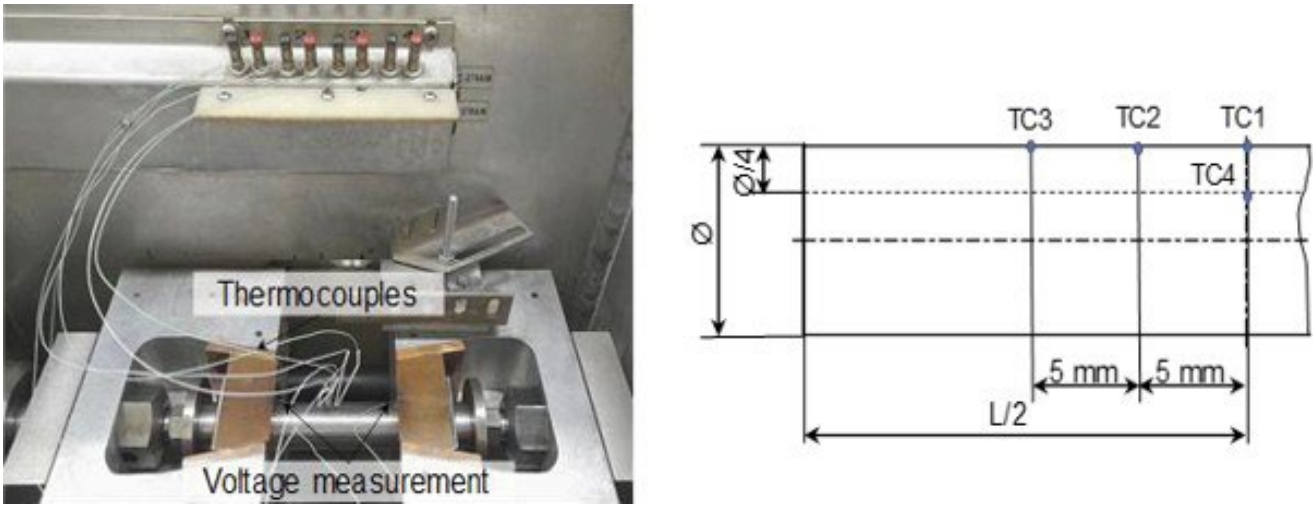

Fig.3 - Experimental setup and points for temperature measurement during conductive heating tests (MCU unit setup).

The aim is to estimate how much of the electrical power is transferred into the sample in the form of heat to quantitatively measure the energy efficiency and give local data sets for evaluation of commercial CENOS software for induction and a new developed simulation tool for inductive, convective, radiative and conductive heating, considering the effect of microstructural changes, oxide scale growth and special electric-thermal contact conditions during heating.

The simulation tool is a Python-based Finite Difference approach for thermal, electrical and micro structural changes and can be directly coupled to the open-source simulation framework PyRolL for roll pass calculations recognizing the resulting inhomogeneity from heating [5].

For comparison purposes the measured power-frequency-time or power-voltage-time and measured temperature-dependent thermo-physical response. Electromagnetic material data were used as input data.

Industrial feasibility studies

Feasibility studies, techno-economic scenario analysis, and equipment assessments were conducted to analyze the optimal layout for the electrification of specific industrial HDG lines and heating system for hot rolling of billets.

The galvanizing line essentially consists of three sections: the entry, the process and exit sections. In the process section, it is fundamental to obtain the desired strip mechanical and surface characteristics, in terms of high-quality galvanizing products through the application of zinc coating and subsequent necessary treatments. The study involves the process section, which currently has a free-flame section (NOF) and a section with natural gas radiant tubes (RT). The application of inductors (with a plant power up to 25 MW) and the potential replacement of natural gas (NG) radiant tubes with electric ones have been considered. A mathematical model of the HDG furnace, based on energy balances and physical relations, was developed

for a gas-fired, IH and electric radiant-tube continuous furnace. The scope of the mathematical modelling activities was to carry out the analysis of thermal energy performance of the continuous annealing furnace and evaluate the energy OPEX cost. CFD simulations have been used to compare performances of electric radiant tubes and NG ones. While flat product heating was explored via induction, for long products a conduction-based approach was also considered. The electrical conduction heating on a large-scale application for billets reheating after Continuous Casting before rolling process has been studied. The main objective is outlined by the analysis of a technological shift from gas-fired reheating to an electric-based one, represented by electrical conduction heating system aiming at improved energy efficiency and direct CO_2 emissions reduction from the production plant. Several plant layout configurations were analyzed through thermodynamic simulations to evaluate the billet thermal profiles under various operating conditions. Different power inputs and target steel temperatures have been considered. The combination of gas combustion and conduction heating was studied with the main aim of optimizing flexibility and performance within existing plant constraints.

RESULTS

The core results from both experimental and numerical work were analyzed. Laboratory-scale tests investigated the thermal behavior of flat steel alloys processed in HDG lines, varying heating rates and soaking conditions while performing metallurgical examinations to assess microstructural changes. At the same time, IH experimental trials on billets were carried out at different power and frequency values to map the thermal response of the materials. The experimental findings were further integrated with feasibility studies investigating the viability of deploying induction and hybrid configurations at a larger scale, for both flat-product lines and billet reheating furnaces, with emphasis on energy performance, metallurgical robustness, and compatibility with existing process architecture.The laboratory activities established correlations between inductor power and heating rates for the different steel grades studied. Microstructural analyses revealed how different heating parameters influence secondary phase recrystallization in steel designed for hot-dip galvanizing (HDG) applications. Microstructural and mechanical characterizations of the flat samples treated at the pilot line after IH with high HR showed IF samples reached a complete recrystallization and mechanical properties typical of extra-deep drawing grades for temperatures ≥ 780°C (figure 4). However, plastic anisotropy values (r) were lower than those found after conventional annealing (1.0 - 1.5 vs. 1.9 - 2.2), suggesting focusing on a study of the texture development as a next investigation step.

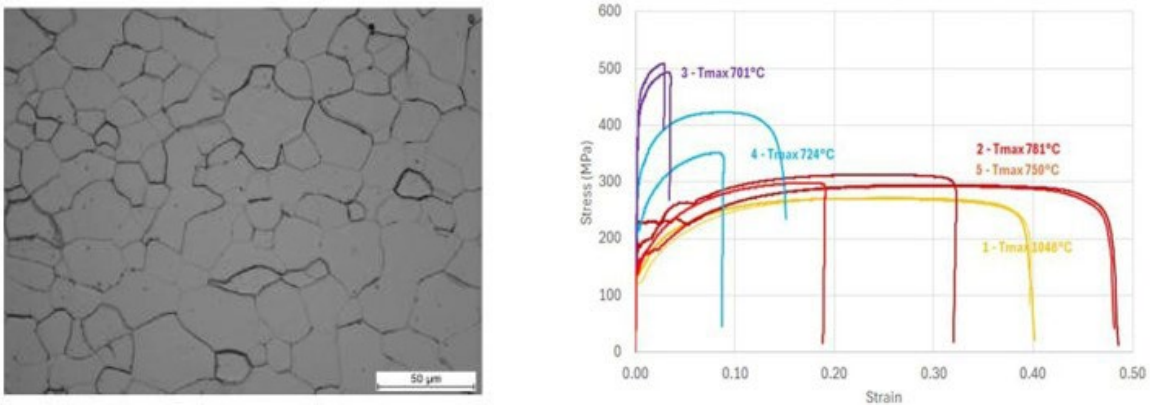

Fig.4 - Microstructure and tensile properties (stress-strain curves) obtained for IF steel.

DP steel achieved a complete recrystallization and tensile properties complying with the standard requirements after heating at temperatures ≥ 780°C (figure 5). S steel is almost completely recrystallized and achieves mechanical properties in line with the standard requirements with heating temperatures around 770°C but exhibits fair elongation values already with a temperature of 720°C.

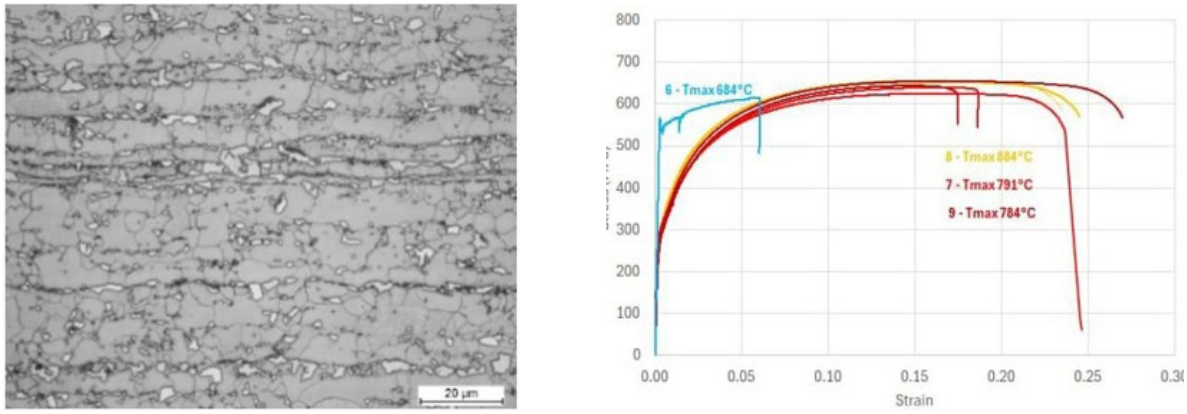

Fig.5 - Microstructure and tensile properties (stress-strain curves) obtained for DP steel.

The analysis of metallurgical changes occurring in the samples structure, after applying thermal cycles through Gleeble machine, resulted in interesting process insights. In IF steel, heating rate significantly affected static recrystallization kinetics, with heating rates below 100 °C/s enhancing recovery and delaying recrystallization due to reduced dislocation density. In such cases, lower yield stress (Rp0.2) and ultimate tensile strength (Rm) values were obtained, with associated coarse ferrite grains and TiC particles growth. Statistical analysis based on data from DP experiments revealed that higher heating rate and lower soaking temperature increased Rp0.2, while Rm was enhanced by longer soaking and higher cooling rates. In addition, faster cooling rate and shorter soaking times improved total elongation (At). These are composed of recrystallized and non-recrystallized ferrite, martensite and bainite. An example of the analyzed microstructures is shown in in figure 6. The fraction of non-recrystallized ferrite is low and increases with decreasing soaking temperature. Similarly to DP steel, in S steel Rm was enhanced by lower soaking temperature and shorter time, while total elongation increases as soaking and galvanizing duration rise.

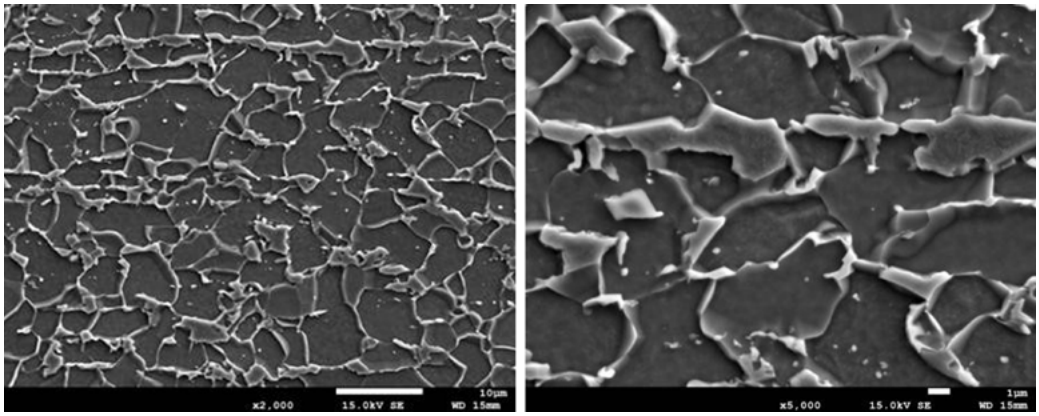

Fig.6 - Microstructure of DP sample after physical simulation of HDG.

On the other hand, initial tests on billet induction heating confirmed the impacts of frequency and power on heating efficiency, electromagnetic field penetration, and field strength. Experiments showed the highest heating rates occur below the Curie temperature of 760°C, which is related to a max recorded power of 86 kW and subsequently decreasing to 25 kW with the raising temperature. Above the Curie point a tangible drop in heating efficiency is observed. This is mainly due to a behavior change of the material, from ferromagnetic to paramagnetic, reducing its

magnetic permeability (μ), limiting eddy currents generation and consequently the heat input. As a result of the comparative calculations, it was found that larger deviations occurred in the range of the Curie temperature when calculated with electromagnetic and thermophysical data from material databases or thermodynamic calculations (PyCalphad). These deviations in the range could be attributed to the differences in the magnetic contribution during the specific heat storage capacity. With the use of measured material data this effect is not observable as shown in figure 7.

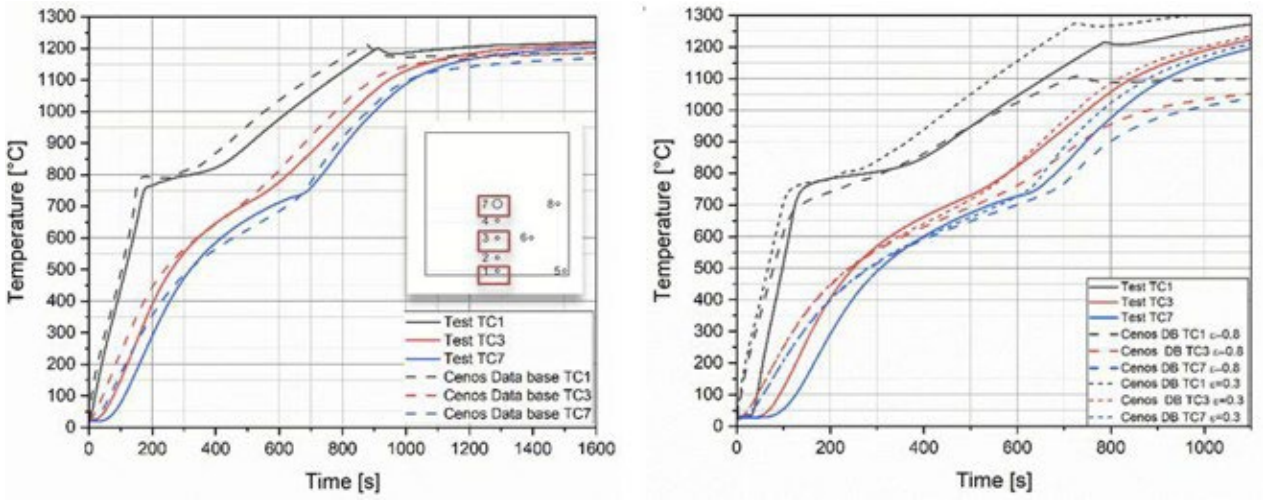

Fig.7 - Comparison of measured a calculated (CENOS®) temperature-time at different position in the inductive heated cross section of a 160x160mm billet for a given heating sequences (left: 100kW electrical power input starting with a machined surface; right: 150kW electrical power input starting with a pre-oxidized surface from 100kW test calculated for different emissivity values (0)).

Moreover, tests demonstrated that increasing the power from 100 kW to 150 kW does not yield proportional reductions in heating time to the austenitizing temperature. This saturation suggests that further power input results at first in increased thermal losses. Notably, the study revealed that further increase of coupling power beyond certain limits did not correlate with accelerated heating, indicating potential efficiency thresholds in the energy dynamics between inductor and billet.

Conductive heating trials resulted in a pronounced thermal gradient on them, with surface-to-core differences up to 530 °C in Ø10 mm and up to 364 °C for the Ø25 mm in cylindrical specimens and temperature asymmetries in square-section specimens. This is mainly due to forced cooling near clamps and uneven current distribution. Numerical simulations were then compared to the measured temperatures, showing strong agreement with them. Since oxide scale growth affects thermal distribution, especially in inductive heating where the maximum heating power is introduced close to the surface. An oxide growth and modified heat transfer model was implemented in the simulation tool for this purpose and is currently in the test phase. Initial results show a noticeable improvement in the agreement between the measured and calculated temperature curves. Critical points within the electrical contact are the contact conditions of the clamps to rough and oxidized surfaces. The current investigation tries to optimize the contact geometry and clamp material for a reduced tool wear during the heating cycle.

From the large-scale point of view, technological suitability studies showed interesting results. The studies on the HDG lines for flat products had the main objective of selecting the best sustainable option (best techno-economic option) for the hybrid heating of the annealing furnace. Simulations suggested that the implementation of inductors alone would not significantly impact the metallurgical effects, although they would provide benefits in cost and energy efficiency. The configuration made up of a complete replacement of gas radiant tubes with electric ones, a small inductor (2.5 MW), and an increased pre-heating section showed the potential for a maximum CO_2 reduction of 32%.

Tab.4 - HDG line analysis: hybrid heating case studies.

Case study	Nr of inductors	Inductor power [MW]	Free Flame zone	Radian tube type	CO_2 reduction [%]
1 (actual furnace)	0	0	Gas	Gas	0
2	1	2.5	Gas	Gas	18.8
3	0	0	Gas	Electric	26.6
4	1	2.5	Gas	Electric	32.2

Energy OPEX analysis demonstrated that while induction heating can achieve higher heating rates (up to ~600°C with 15 MW for HSLA strips), its implementation alone requires significant electrical power (up to 25 MW to fully replace NG heating), leading to high operational costs and demanding a larger furnace footprint. Despite limited metallurgical impact and no gain in line productivity due to downstream constraints, hybrid solutions combining induction with electric radiant tubes were identified as more sustainable. The analysis revealed that hybrid furnace OPEX becomes lower than conventional NG heating when the electricity-to-gas price ratio falls below 2.5, making energy cost competitiveness highly dependent on market conditions. CFD/FEM simulations proved that electric radiant tubes could deliver the same thermal power to the furnace as gas tubes, but with lower maximum and average temperatures of 965 vs. 1011 °C (66% energy efficiency).

Adding to that, electric tubes provided a more uniform heating of the steel strip. Simulation activities and layout analysis to identify an optimized system configuration for billet reheating were conducted. Based on specific layout constraints, a basic and detailed design of the conductive heating system was completed. Main results of these activities showed feasibility of reaching target temperatures in line with the process requirements. The selected configuration is expected to reduce the amount of natural gas consumption and direct CO_2 emissions.

NEXT STEPS

Next project steps on the experimental pilot line for flat products will be performed in a controlled atmosphere and with an additional furnace section guaranteeing soaking time maintenance. An inert gas will be used to study the rapid heating treatment effect on different steel-grade surfaces.

Further experiments will focus on extending the validated billet induction heating models to larger-scale systems operating at higher power levels and lower frequencies under industrial conditions. Experimental activities on full-size billets (150X150 mm and 160X160 mm) in a vacuum induction furnace are planned to generate T-t profiles for advanced model validation. Additional parameter studies will explore the influence of initial inhomogeneities, heat source distribution, contact conditions, and microstructural evolution on heating strategies. In parallel, conductive heating tests will be expanded using improved current control, inert atmospheres to reduce surface oxidation, and varied sample geometries, aiming at producing specimens with tailored microstructural states.

These activities will support the optimization of hybrid heating systems and enable reliable process transfer from laboratory to pilot scale. Furthermore, various combined heating processes are analyzed for their energy efficiency. A thermal and microstructural coupling of the heating tool with the simulation framework PyRolL will be used to analyze the influence of the heating state on groove pass design of the first passes and the point of independence from heating conditions within a roll pass sequence. The implementation of a 2.5 MW inductor in the HDG furnace will be part of an optimized hybrid heating system, designed to improve energy efficiency and reduce CO_2 emissions.

Despite space and power constraints, the basic design phase has demonstrated feasibility. Further R&D activities will validate system performance under real conditions.
A conduction heating system was designed and prepared for pilot installation in 2025. The main objective will be to reach the assessment of the final large-scale solution able to run the new technology in the frame of the production

scale. Moreover, a feasibility study of the innovative proposed solution will be carried out in an additional specific plant layout.

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