1.4 MIMESIS – Mathematics and Materials Science For Steel Production and Manufacturing

Najib Alia, Prerana Das, Dietmar Hömberg, and Volker John

Introduction

Almost all manufacturing sectors, from construction to transport to consumer goods, are largely based on the utilization of steels. Steel products often compete favourably with alternative material solutions in cost efficiency and life cycle analyses. The last fifteen years have seen the development of ever more refined high-strength and multiphase steels with purpose designed chemical compositions allowing for significant weight reduction, e.g., in automotive industry. The production of these modern steel grades needs a precise process control, since there is only a narrow process window available in which the desired physical properties are defined. In combination with component walls getting thinner and thinner, these new steels make also new demands on a more precise process control in metal manufacturing processes, such as welding and hardening.

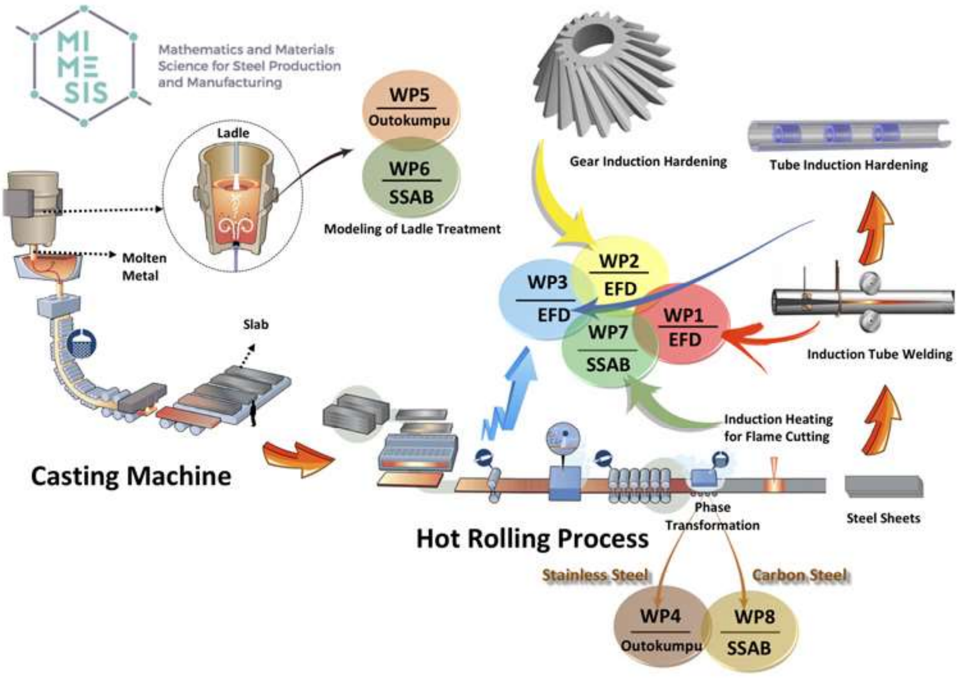

Fig. 1: *MIMESIS – Ph.D. projects in a nutshell*

Improved and optimized process control requires quantitative mathematical modeling, simulation, and optimization of the complex thermal cycles and thermal gradients experienced by the processed material. Such models require an understanding of the behavior of the materials from a materials science and phase transformations perspective. Unfortunately, it is almost impossible for companies to find graduates combining deep knowledge in materials science with expertise in mathematical modeling, simulation and optimization.

To fill this gap, five partners from steel production (Outokumpu and SSAB in Finland) and steel manufacturing (EFD Induction in Norway), from materials science (University of Oulu, Finland) and applied mathematics (WIAS) established the European Industrial Doctorate program on *"Mathematics and Materials Science for Steel Production and Manufacturing (MIMESIS)"*, where eight Ph.D. projects are jointly carried out. The students spent at least 18 months with an industry partner, thereby encouraging inter-sectoral mobility. Finally, the project has a clear interdisciplinary makeup: Four Ph.D. students are from materials science and four from mathematics.

The research is focussed on three major topics along the process chain for steel production and manufacturing. Two theses are related to secondary metallurgy in the ladle considering computational fluid dynamics models of ladle treatments (WP5) and optimal control of ladle stirring (WP6, see the subsection on optimal control of ladle stirring), and two theses are concerned with phase transformations during steel production (WPs 4&8). Two theses concern the induction hardening process: One is on the hardening of helical and bevel gears by an optimized single or multi-frequency approach, and the other is a novel idea about the hardening of the inner surface of pipes (WPs 2&3). One thesis studies a prototype set-up for inductive pre- and post-heating in the thermal cutting of steel plates and one is related to high-frequency welding of steel tubes (WPs 1&7). The latter will be discussed in more detail in the subsection on modeling and simulation of tube welding.

A specific highlight of the programme were customized three-month courses on steelmaking, physical simulation and testing of steels in Oulu and on numerical simulation and optimization in Berlin. Additionally, the early stage researchers also had tailored on-site industrial trainings offered by three industrial partners.

Optimal control of ladle stirring

Ladle stirring is a process of steel-making where liquid steel is stirred by a gas injected from the bottom of the tank (ladle). The objective of the project is to improve the control of ladle stirring to enhance the cleanliness of liquid steel. The objective will be reached by developing a numerical model together with vibration measurement systems to monitor the actual stirring and optimize it. Better control of stirring gives a possibility to reduce the formation of non-metallic inclusions and to optimize the treatment time and gas consumption during the process.

Fig. 2: *Photo of the experimental ladle in the laboratory of the University of Oulu*

Numerical model of a laboratory-scale ladle stirring. Making measurements during ladle stirring in real industrial conditions is a complex task due to the extreme environment. It is, therefore, usual to reproduce the process in laboratory conditions by using water instead of liquid steel and air instead of argon gas (see Figure 2).

A numerical model is developed in order to study and optimize mathematically the stirring flow. The flow is computed using the single-phase incompressible Navier–Stokes equations for the liquid steel and a buoyancy force for the gas phase [1] (see Figure 3). In addition, the Smagorinsky turbulent viscosity is applied to resolve the turbulence of the flow (Reynolds number $\sim$ 100,000). The model is solved with the in-house code ParMooN developed by RG 3 *Numerical Mathematics and Scientific Computing* [2].

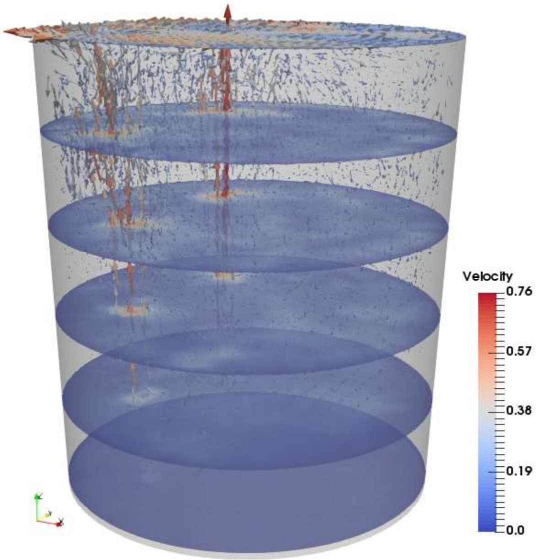

Fig. 3: *Numerical ladle stirring: Snapshot of the velocity field computed with* ParMooN *with the Smagorinsky turbulent model*

One reason of simulating a laboratory-scale ladle rather than an industrial one is the availability of experimental measurements. They can indeed be advantageously used to adjust numerical parameters, such as the turbulent viscosity constant, and to validate the model (see Figure 4). The results obtained so far show how simplified modeling assumptions (two-phase flows reduced to a single-phase flow) can lead to reasonable results.

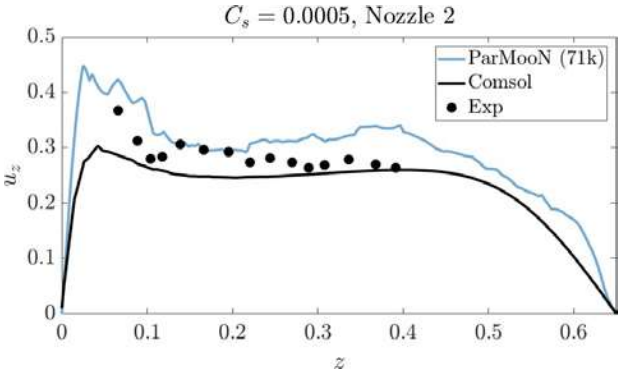

Fig. 4: *Validation of the numerical flow model: Comparison of the vertical velocity component between numerical results and experimental measurements*

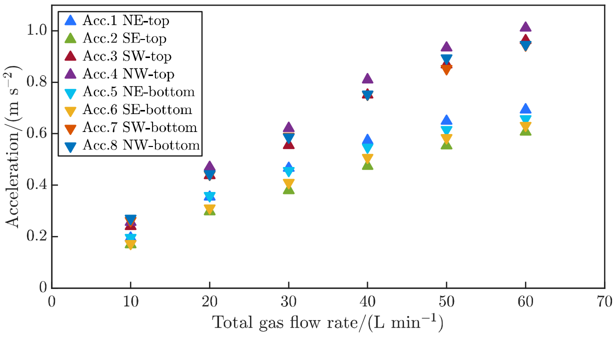

Fig. 5: *Evolution of RMS values of vibrations with gas flow rate*

After validating the numerical model, the objective is to formulate and to solve an optimal control problem to make the stirring more efficient. Several control parameters are considered, e.g., the intensity of the gas flow rate, its evolution in time, or the position of the nozzles. The solution can then be used in combination with vibrations measurements to make the operations more efficient and easier to control for the operators.

Experimental vibrations measurements. In this project, in addition to the numerical investigation, an experiment was conducted using vibrations sensors on the ladle wall. Since it is of industrial interest to use the vibrations to monitor and control automatically the process, it is of importance to study the vibrations signals measured by accelerometers, the relationship between the mixing intensity in the steel bath and the vibrations level, the effect of the sensors' positions on the signals, etc. It is shown, for example, that the vibrations increase significantly with the injected gas flow rate (see Figure 5). Moreover, the position of the accelerometers has an influence on the measured signal. By placing several sensors at relevant positions, it is possible to describe precisely the mixing intensity in the ladle, as well as stirring problems, such as gas nozzle clogging or loss of stirring efficiency.

Modeling and simulation of tube welding

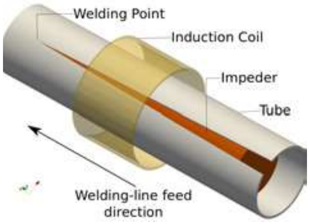

Fig. 6: *High-frequency induction welding of a steel tube*

High-frequency induction welding is widely used, especially in the production of superior quality oil and gas pipes and structural tubes. A steel strip is cold-formed into a tubular shape in a continuous roll forming mill. The strip edges are electromagnetically heated and joined mechanically by pushing the strip edges against each other to form the longitudinally welded tube (see Figure 6).

The welded joint, as seen in the transverse cross section of a welded tube, is a very narrow zone compared to the tube diameter. The strip edges are heated to almost melting temperature and are pushed against each other in the viscoplastic state to form the welded joint where crystallographic texture and microstructural changes appear.

The electromagnetic heating of the tube is analogous to transformer theory. The coil is the primary current source, the strip is where the current is induced, and the impeder acts as a magnetic core. The entire setup, coil current and frequency determine the amount of the induced current in the tube.

High-frequency alternating current is supplied to the induction coil. This induces eddy currents in the strip under the coil. The induced current can follow the principal paths indicated in Figure 7 to complete the circuit. Along the strip edges, it can flow downstream from the coil towards the welding point or away from the coil in the upstream direction. At any strip cross section, the current can follow a path either along the outer circumference or the inner circumference. The goal of high-frequency induction welding is to maximize the current density in the strip edge downstream, towards the welding point.

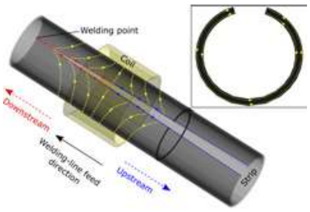

Fig. 7: *Schematic current path in the tube*

The relative positioning of the strip, induction coil, and impeder is very important to obtain an efficient heating process. The geometric shape of the opening between the strip edges is usually a Vee shape. Sometimes it is distorted by spring-back due to the mechanical forming of the strip. This also affects the current distribution. Further important process parameters are the coil current and welder frequency.

For a better understanding of the complex interactions between the above parameters, numerical simulation is an indispensable tool. In [3], we present the first comprehensive simulation approach for high-frequency induction welding in 3D. Its main novelties are a new analytic expression for the space-dependent velocity of tubes accounting for arbitrary Vee-angle and spring-back and a stabilization strategy, which allows us to consider realistic welding-line speeds.

Mathematical model and numerical realization. The mathematical model comprises a harmonic vector potential formulation of Maxwell's equations and a quasi-static, convection-dominated heat equation coupled through the Joule heat term and nonlinear constitutive relations.

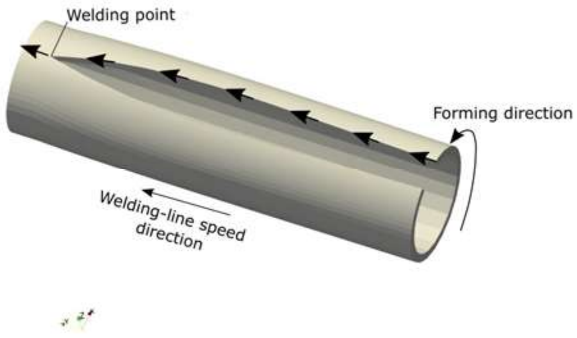

Fig. 8: *Local velocity to represent feed velocity and forming*

An important effect that needs to be accounted for is the computation of velocity in the strip. After the welding point is reached, the velocity has only a component in the feeding direction, while before, the velocity varies locally with non-vanishing radial and angular components. To obtain the correct temperatures especially close to the strip edge, it is crucial to use the correct locally varying velocity for the simulation. Figure 8 shows the resulting local velocity vectors for selected points on the strip opening for a spring-back tube opening. Instead of a constant velocity solely in y-direction one can see that now the velocity follows the contour of the opening; for details, we refer to [3].

The heat equation is discretized by linear nodal finite elements. To account for high speeds somewhere in the range of 40m/min to 200m/min, the Streamline Upwind Petrov Galerkin (SUPG) method is used. The discretization of Maxwell's equations is done with Nédélec elements of lowest order. The magnetization depends both on the temperature and the magnetic field. For fixed temperature this nonlinearity is resolved numerically based on an averaging approach [4]. The coupled system is iteratively decoupled and solved using a fixed-point iteration.

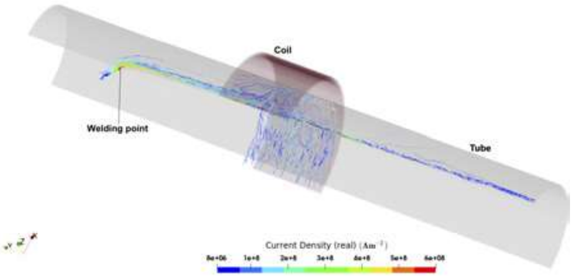

Fig. 9: *Current path in the tube*

Simulation results. Figure 9 shows the current density distribution in the strip edge with current concentration both in the downstream and upstream directions and a maximum close to the weld point. Examples of temperature distribution in the welded strip are depicted in Figure 10 for two different Vee-openings and a spring-back distorted opening. The strip edges are heated to very high temperatures because of Joule heating from eddy current concentration. The velocity function incorporates the mechanical forming of the strip into a tube in addition to the welding-line velocity.

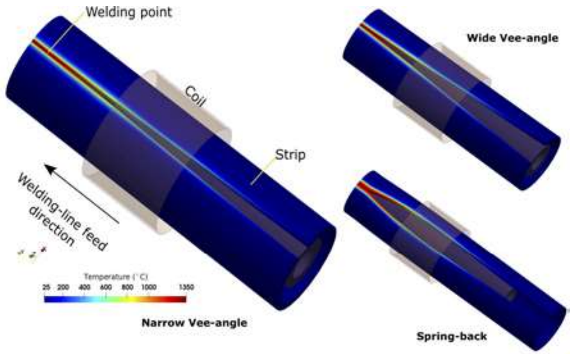

Fig. 10: *Temperature distribution in the tube for different openings*

Conclusion and outlook

Concerning the optimization of ladle stirring, the project revealed how complex the industrial problem is, and how important it is to decompose the different issues into different steps and work on simplified aspects of the problem, e.g., laboratory-scale experiment instead of real ladle and single-phase flow instead of multiphase flows. The experimental vibrations measurements have led to innovative ideas which were not considered so far in the industry, namely, use of several sensors simultaneously and at different positions to have a more precise knowledge of the actual stirring in the ladle.

The next step consists of implementing such ideas in the industrial process. Several opportunities appear from the perspective of applied mathematics: Modeling and computation of the fluid-structure interaction to predict the vibrations level of the ladle, or application of deep learning techniques to analyze the big amount of data measured by the vibrations to find out the vibrations level corresponding to optimal stirring.

For high-frequency induction welding a three-dimensional model has been developed. It is a nonlinearly coupled system of Maxwell's equations and the heat equation. The results show a temperature distribution in the strip edges that develops as expected from previous studies and visual observations of the process. A wider Vee-angle results in a wider heat-affected zone. Increasing the frequency reduces the width of the heat-affected zone.

This new three-dimensional simulation tool will provide a basis for an optimization of the design of the welder, especially with respect to the dimensioning of induction coil, impeder, and the configuration of these relative to the steel strip. Future work will include the study of the mechanics of the material squeeze-out when the strip edges are joined together after heating.

References

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