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## Design of an one-sided transverse flux induction coil by using a numerical optimization algorithm

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### Abstract

The transverse flux heating (TFH) concept offers very high electrical efficiency in combination with unique technological flexibility. Numerous advantages make this method beyond competition to be applied in e.g. continuous strip production and processing lines. However, all potential advantages of TFH can be realized in practice only by optimal design of the inductor shape and optimal control of the heaters, using numerical modelling and optimization techniques.

The paper describes a successive approach to optimal design of a single layer induction coil, which will be used for one-sided TFH of moving thin steel strip with constant width. The peculiarity of the design refers to the very slow movement speed of the strip and the target temperature, which is set below Curie.

**Key words:** induction heat treatment, one-sided transverse flux heating, strip heating, numerical optimization

### Introduction

The continuous heating of thin metal strip is an important process step in many industrial production lines. The areas of application of strip heating ranges from heat treatment, coating and drying of sheets and strips to the use in slab and casting plants for intermediate heating before milling. The thicknesses of the strip could vary between 0.1 mm and 60 mm at widths up to 2000 mm. Due to the different fields of application of strip heating for a wide variety of materials, the strip temperatures to be achieved are in the range of a few 10 °C for drying and up to 1200 °C for hot-forming. The manufacture of semi-finished products of different composition and qualities often requires a heat treatment, such as tempering, annealing or galvannealing in order to achieve desired material properties. Due to targeted heating, different degrees of hardness, grain sizes or surface textures can be set. The use of sheet and strip as semi-finished products is particularly important in the metalworking industry, e.g. the automotive or electrical industry. [1]

Commonly used materials are non-magnetic metals such as copper, brass and aluminum, precious metals such as gold and silver, and various steels and alloys. [2]

Today, conventional heaters such as gas or oil fired furnaces are still widely spread. All of these installations are working by the principle of heat transfer to the workpiece through the surface. Based on the laws of thermodynamics, the atmosphere in the oven always has to be warmer than the goal temperature of the workpiece. Although this technique ensures homogeneous and through heating of the material, there are a variety of disadvantages and restrictions like the large size of the installations, long heating time, high thermal losses, limited power density and speed of motion, intensive scale formation on the materials surface and environmental pollution.

Considering the aspect of time, on the one hand for the heating of the material and on the other hand the warm-up and cooling time of the furnace, a high waste of energy and inflexibility for the integration in modern production lines is deduced.

Induction heating offers solutions to the above mentioned disadvantages and restrictions of conventional heaters. Based on the direct and contactless heating, the heat is generated directly inside the workpiece. The advantages are amongst others theoretically unlimited power density, very short heating times, low floor space, easy and fast process control.

For the heating of continuous moving metal strip, two processes have become established in industry: the longitudinal flux heating (LFH) and the TFH. Both methods are based on the same heating method, but differ by the direction of the magnetic flux, which is parallel to the workpiece plane for LFH and normal for TFH. Due to the different flux orientation, the eddy-currents are also induced in a different way. For LFH the eddy-currents are flowing in the cross-section of the metal strip. Especially for thin metal strip the LFH is limited by the penetration depth and furthermore by the frequency. If the penetration depth is not small enough, the induced eddy-currents may cancel out each other. Since the eddy-currents in the TFH flow in the surface of the metal strip, there is no limit to a decrease of the strip thickness and is thus particularly suitable for the heating of thin metal strip. In addition to this the induced current flows as an image of the inductor shape, which gives the opportunity to control the Joule heat distribution inside the metal strip and thus the temperature distribution.



### Characterization of a transverse flux heating system

The typical setup of a TFH system consists of a symmetrical arrangement of two induction coils and if necessary of two adapted flux guiding elements, one above and the other below the metal strip. Neglecting connections to the generator, Fig. 1 shows a principle sketch of a TFH heater.

The characteristic dimensions of a TFH system are given by the pole pitch  $t$ , coupling gap  $h$ , length of the induction coil  $b_i$ , width of the induction conductor  $a_i$  in the regular zone and  $a_{je}$  in the coil head zone (can also exist of two or more windings if the gap between each conductor is much smaller than the width of the conductor). The influence of these geometrical parameters have been examined in [1-3].

The following shows how to design successively a one-sided TFH coil by using two-dimensional and three-dimensional numerical simulations and optimization.

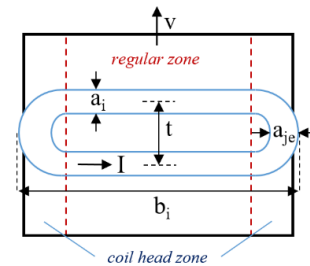


Fig. 1: Typical setup of a TFH coil.

### Defining the goal and analytical preliminary investigation

The main goal of the inductor design is to achieve a homogenous temperature distribution with a specific setpoint temperature  $T_{sp}$  in a defined distance  $d_{sp}$  after passing through the inductor. The width and the thickness of the strip are fixed. A second goal is the demand for a robust and constructible design. In order to determine a suitable starting range for the geometrical dimensions of the inductor, expert values or the available space for the integration of the inductor into the system can be used. The latter is a compromise between a filigree and a maximum possible dimension of the inductor. Important geometrical parameters that have to be dimensioned are the conductor profile and the pole pitch  $t$ . From these dimensions all further distances can be derived based on the investigations of [1] and [3].

### 2D numerical modelling of the regular zone

The next step in inductor design involves two-dimensional numerical investigations on the infinitely wide strip. As a result, an infinitely wide regular zone of the TFH inductor is mapped. These calculations are made with ANSYS Mechanical additionally using the electromagnetic package. Fig. 2 shows a close-up of the regular zone of the two-dimensional numerical model based on the predefined inductor concept. The electromagnetic Modell (EM) can be used to calculate (harmonic solution) the optimum frequency for the best electromagnetic coupling between the inductor and the workpiece and thus the maximum electrical efficiency. Furthermore, sensitivity studies on the influence of e.g. the coupling gap, the strip thickness or the influence of the magnetic permeability ( $\mu_r$ ) of the strip can be executed with little computational effort.

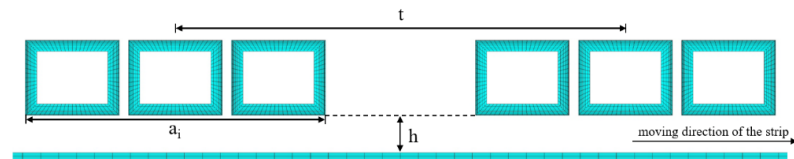


Fig. 2 Sketch of the two-dimensional electromagnetic numerical model.

Fig. 3 shows the results of an exemplary frequency analyses. It is typical for TFH, that there is a wide range of frequency wherein the electrical efficiency is changing less. For higher frequencies, the penetration depth is decreasing and the heating behavior is changing from TFH to LFH [1-4]. Within these frequencies, a special feature of TFH is that it is not sensitive to the magnetic permeability of the strip material. This is shown in Fig. 3 and is especially of interest if the magnetic data of the steel strip is not exactly known and the maximum temperature does not exceed Curie-temperature.

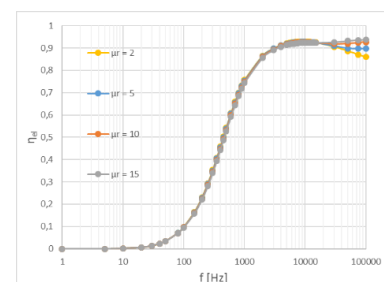


Fig. 3: Sensitivity studies of the electrical efficiency for different magnetic permeability of the strip.

Subsequently, investigations are carried out on the moving strip by means of a transient thermal analysis. The necessary thermal model (TM) consists only of the strip and is coupled with the Joule heat sources of the EM. Convective heat losses and radiation losses on the bottom and top of the strip are taken into account. The strip movement is described by means of a procedure which is performed after each transient calculation step. Each nodal temperature value is shifted by a distance in the direction of movement, which results from the velocity  $v$  and the time step  $t$ . If the shifting distance is smaller or bigger than the distance between the nodes, the value gets linearly interpolated. For this procedure a mapped meshing of the strip is required. Now, the inductor current must be set, to reach the desired target temperature  $T_{sp}$  at the point with the distance  $d_{sp}$  behind the inductor. For this a manual parameter study or an automated evaluation can be done. For the latter, e.g. a loop can be used that calculates multiple current flows. Based on the results, the needed current can be interpolated. A typical TFH surface temperature distribution along the strip moving at speed  $v$  is shown in Fig. 4.

This concludes the preliminary two-dimensional investigations and initial estimates for the expected power range and costs for peripheral elements such as generator and resonant circuit can be done. Since an idealized system was calculated until now and losses due to the coil head and connections must be added to the manufactured TFH system, the assumed power should be increased by some percent to gain a representative value.

### Three-dimensional electromagnetic and thermal modelling

The next step in coil design involves numerical studies on the three-dimensional EM (harmonic solution) and TM (transient solution). This step is necessary to map the influence of the coil head on the strip edge effects. Due to the symmetrical structure of the TFH system, it is possible to examine a quarter- or a half model. This saves computing time and enables a fast and in case of the half model a yet physically correct simulation of the heating process. Fig. 5 shows examples of both model types for a round coil head. Other possible head shapes are e.g. rectangular or lamp shape. To ensure that the frequency analysis from the two-dimensional EM model has yielded a comparable result for the quarter or half model, in Fig. 6 the frequency analysis for the three-dimensional half-model with the two-dimensional model for an exemplary calculation with the same material properties is compared. The figure shows that the electrical efficiency in the three-dimensional model is lower. This is due to the coil head losses, which are not shown in the two-dimensional model. However, the optimal frequency is in the same range. The aim of this investigation step is to design the coil head in such a way that the temperature distribution with the target temperature  $T_{sp}$  in a distance  $d_{sp}$  after passing through the inductor is as homogeneous as possible. To achieve this, an automated optimization algorithm will be used.

### Numerical calculation of the coil head using a genetic optimization algorithm

The used optimization algorithm is a genetic algorithm, which is characterized by the fact that the global minimum is found within a given range for three different parameters. The exact mode of operation is described inter alia [5,6] and the optimization structure is shown in Fig. 7.

Before the optimization procedure is started, the three-dimensional EM and TM must be parameterized. Based on the results of the two-dimensional examination, initially parameters are selected that have an influence on the coil head area. A good start is the inductor length  $b_i$ , the inductor cross-section  $a_{je}$  and the current. This choice ensures that the regular area remains unchanged, thus remaining comparability between the models. The next step before starting the algorithm is to set the range for each parameter. A good estimate to use for the current is the calculated value from the two-dimensional calculation as a lower limit and the same value plus 20 % as the upper limit. The current is needed to reach the target temperature  $T_{sp}$ . A possible choice for  $a_{je}$  is to narrow and enlarge the actual value each by 20 %. For the parameter range of  $b_i$ , the values chosen are those which, at the lower limit, ensure that the coil head is completely inside the strip and with the inner winding outside the edge of the strip as an upper limit. Fig 8 shows the successive approach to the optimal coil design step by step.

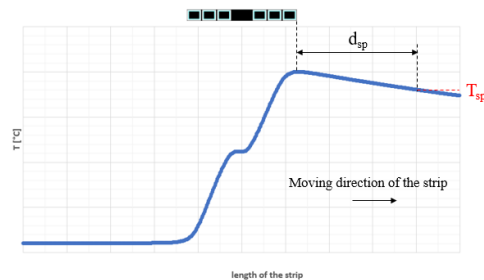


Fig. 4: Quasi-stationary temperature distribution along the surface of a moving strip.

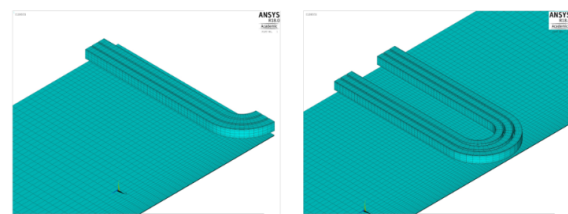


Fig. 5: Example of a quarter - (left) and a half model of a TFH coil (right).

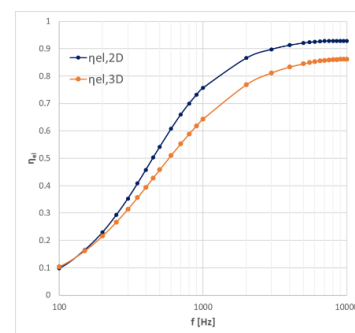


Fig. 6: Comparison between two- and three-dimensional frequency analysis.

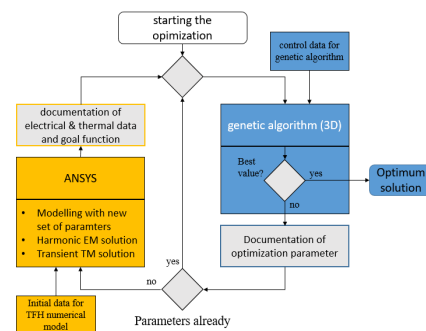


Fig. 7: Structure of optimization procedure.

“Step 1” includes an optimization based on the integral Joule heat source distribution (JH) using a quarter EM. The JH is normalized to the maximum value in the regular zone in order to obtain a qualitative course of the heat source distribution and thus to ensure a good comparability of the goal function. With the simulation computer used a duration of about five minutes per each optimization step in test examinations on a EM with 180,000 elements was reached. The temperature distribution was then validated on a half model and a maximum temperature deviation of 15 % could be determined. When analyzing the optimization

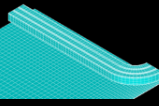
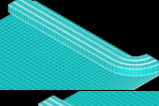

Step 1		<b>EM</b> Optimization based on JH distribution (integrated along the strip)	ca. 5 min per optimization step	+/- 15 % of $T_{sp}$
Step 2		<b>EM &amp; TM</b> Optimization based on temperature distribution in $d_{sp}$ behind the inductor	ca. 15 min per optimization step	+/- 10 % of $T_{sp}$
Step 3		<b>EM &amp; TH</b> Optimization based on temperature distribution in $d_{sp}$ behind the inductor	ca. 30 min per optimization step	+/- 3 % of $T_{sp}$

Fig. 8: Successive optimization approach.

results for each parameter, it should be considered that these are in the middle of their interval. If one or more parameters tend to a limit, the affected interval must be increased in that direction of range violation and the opposite limit can be decreased. Then the optimization has to be restarted. In order to a further reduction of the deviation from the set temperature  $T_{sp}$ , the EM is coupled with TM in "Step 2". The goal function of the optimization algorithm is given by the maximum deviation from  $T_{sp}$ . Due to the transient solution of the TM, the computing time increases to 15 min per step. However, it is possible to reduce the parameter range based on the optimization results from “Step 1”. This makes it possible to find the optimal solution faster. In this step, a minimum deviation from the target temperature of 10 % could be validated on the equivalent half-model. Further minimization is not possible on the quarter model. This is due to the fact that the heat sources on the returning inductor side are not taken into account and thus do not flow into the temperature calculation. For very fast strip movements (e.g.  $v > 10$  m/min), sufficient accuracy can be achieved, as described in [2]. For slow strip movements, integral effects become more influential and analysis on the half model is necessary to further minimize the temperature deviation as it is shown in “Step 3”. In this optimization step, the EM and the TM of the half inductor arrangement are mapped. As a result, the number of elements to be calculated and, therefore, the computing time doubled to 30 min per step. However, the calculation of the goal function has the highest accuracy and also offers the possibility of electrical data e.g. the inductors voltage and inductance. The least deviation that could be achieved with these optimization parameters is  $\pm 3$  %. Further investigation with other optimization parameters combinations may provide further improvement in maximum deviation from  $T_{sp}$ .

## Conclusions

In this paper, a successive approach to optimal design of an inductive transverse flux heating system using numerical simulations and a genetic optimization algorithm is shown. The optimization takes place with respect to a goal function which describes a homogeneous temperature distribution at a defined distance after passing through the inductor. The hierarchical structure that consists of several steps is described. First, a coil concept was set by e.g. expert values. Next, preliminary calculations or sensitivity studies have been carried out based on a two-dimensional numerical model which maps the cross section through the regular zone of the inductor. Amongst others, it has been shown that the transverse flux heating is not sensitive to the magnetic permeability of the strip. In the next step, a three-dimensional numerical model was created, parameterized and coupled with a genetic algorithm. Depending on the temperature homogeneity to be achieved, step by step the complexity of the model and thus the associated computational effort can be increased. Starting with a quarter electromagnetic model, where the goal function is the normalized Joule Heat distribution, this can be extended by an additional thermal model and the goal function can be adapted to the temperature distribution. In a final step with maximum accuracy, the optimization can be carried out on an electromagnetic coupled with a thermal model mapping the half inductor setup. Thus, a successive improvement in accuracy from  $\pm 15$  % to  $\pm 3$  % could be achieved.

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