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Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
Susanne Jakob
Dipl.-Ing. Helge Drumm

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H. Schülbe, A. Nikanorov, B. Nacke

Numerical and Experimental Investigations of High Flexible Transverse Flux Heating Systems

A lot of production processes in metal industry feature as an important processing step the heating of thin metal strips in continuous lines. There are several fields of industrial applications where the heating is needed:

- heat treatment (e.g. hardening, annealing);
- heating for shape transforming (e.g. hot forming, rolling);
- heating for coating (e.g. galvanizing, galvaneeling, lacquering, painting);
- others (e.g. drying, cleaning, cutting).

Nowadays conventional heaters with oil or gas are mainly used in industry. All of them have significant disadvantages and restrictions because of the heating principle, which works by heat transfer through the surface. To overcome the disadvantages and limitations of conventional heaters, the transverse flux induction heating (TFH) technology is an innovative solution. It is based on the principle of contactless heat generation inside the workpiece material. In oposite to the conventional heaters the advantages are, for example, unlimited power density, high efficiency, easy and fast process control, low floor space needs, high flexibility in processing and so on. The TFH concept has advantages even compared to the induction longitudinal heating principle. On one hand this is indicated by working conditions like two decades lower frequency request and the strip not enclosed by the induction coils. On the other hand it has a unique process advantage to heat thin steel products over the Curie-point without limitations.

TRANSVERSE FLUX HEATING

One configuration of the TFH construction is shown in figure 1. The strip to be heated is positioned between two inductors located above and below the strip. Magnetic field created

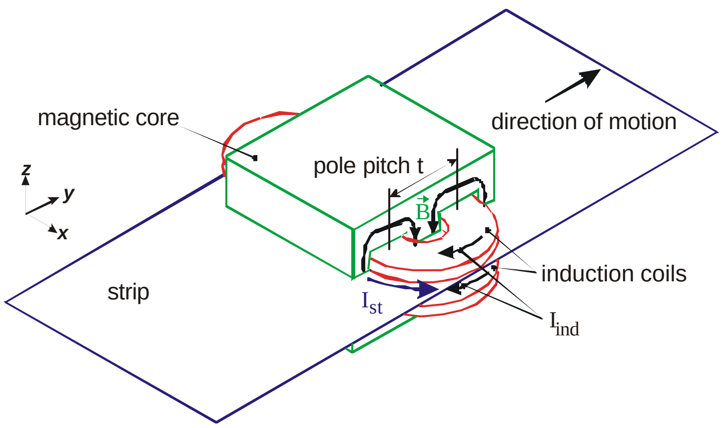

Figure 1. Principle of transverse flux induction heating

by a certain frequency current in the induction coils is mainly oriented orthogonally to the strip surface. Because of this field eddy currents in the strip are induced. They produce Joule heat in the strip material. Depending on the demand, the TFH installations can be accomplished by magnetic flux guiding elements.

By the design of the induction coil it is possible to influence the currents in the strip and by this the temperature, because the eddy currents are, generally, a projection of currents in the induction coil.

The TFH is a well known technology since a long time, but till now it is not used widespread. This is certainly substantiated in the complicate design, where a comparably big set of parameters has to be correctly chosen. Only with the progressive development of computers and advanced numerical tools it is possible now to design these installations with adequate results.

FLEXIBLE CONCEPT

In the past intensive research works of the Institute in the field of TFH were mainly concentrated on heating of strip with constant width. However the industry has a demand for flexible heating systems, which provide different temperature distributions for different strip dimensions and strip materials. The main feature needed in modern production lines is to have a freedom in necessary range of the strip width.

A completely new concept for variable band width inductor (VABID) oriented for this needs has been developed. This system offers unique opportunities to be adjusted to the requirements of different process. The aim for this new development was to create a universal system to heat strip of variable width, thickness and different materials with flexible temperature profiles within one installation. The main principle of the concept is shown in figure 2. By adjusting two independent inductor sections in one layer, a variable modification of the effective inductor is provided. To adjust the induction coil the two inductor sections are orthogonal moved to the direction of movement. To have the same conditions on both strip edges the sections are simultaneously shifted depending on the borders.

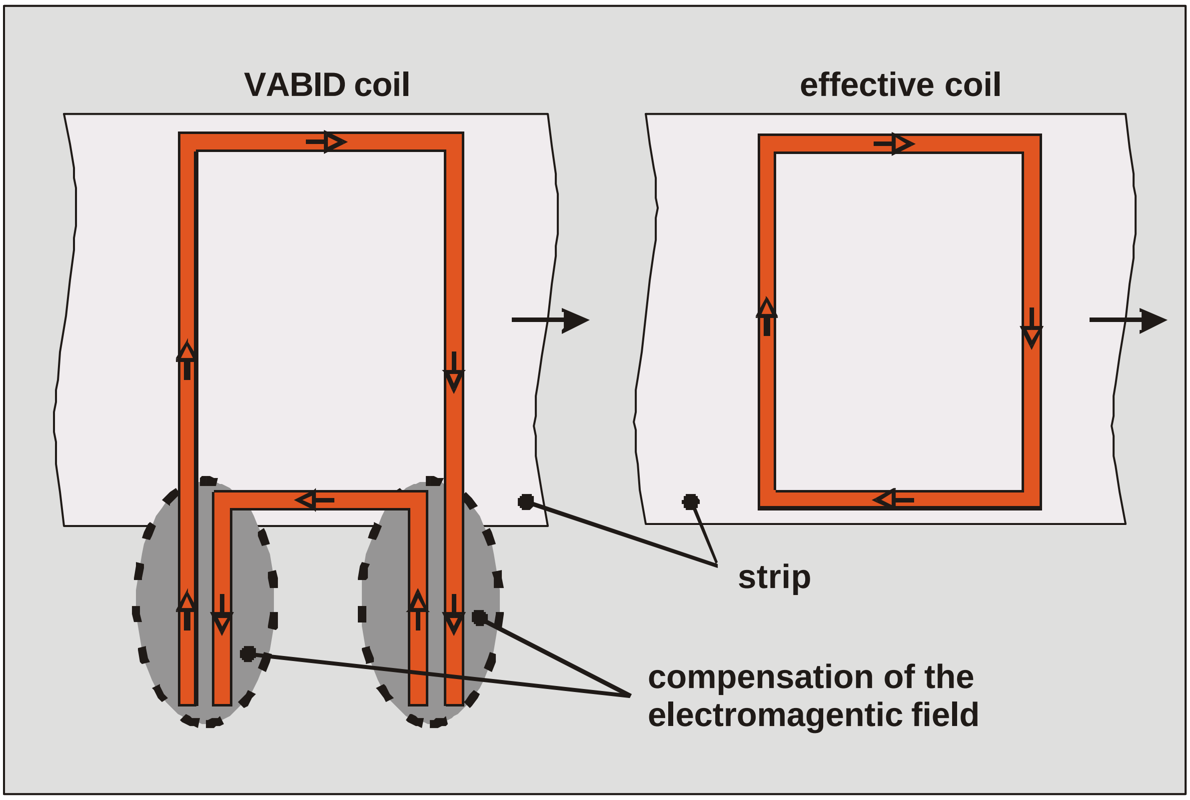

Figure 2. Principle of VABID-concept – layout of one inductor layer and effective coil

By the layout of the inductor sections and by the suitable electrical connecting of them, in the region of the feeding the electromagnetic field is quasi compensated by itself. From this an effective inductor looks like it is represented on the right in figure 2.

An important aspect for the design of transverse flux heaters is the organization of the coil head, i.e. the form of the inductor in the range of the strip edge [2]. In order to be able to take into account this, several of the described inductor layer are used. It is reached by individual positioning of each inductor section from all layers so, that the effective coil head can be adjusted. In this way the system can be adapted for different materials or dimensions of the strip. The more inductor layers are used, the finer the coil head can be adjusted. At the same time the complexity of the installation is substantially increased, because all inductor sections must be independently positioned.

Depending on the needs for the heating process, the VABID-system can be arranged in different ways. To reduce the complexity of the installation, the possible process control channels (degrees of freedom) can be reduced to only one. On the other hand, if full flexibility is needed, the VABID-system can be applied with adjusting all process control channels:

- ***One degree of freedom (thickness)***

  Only the thickness of the strip material is variable. This can be adjusted by adapting frequency and of course the power of the power supply. The design of the induction coil is fixed for one variation of the strip width.

- ***One degree of freedom (width)***

  In the case of processing a variable width of the strip, it can be realized by shifting the complete coils of each strip edge together. This means, that the inductor sections on one side of the strip are combined and moved together depending on the edge of the strip. Therfore there are only two parts to be adjusted mechanically. The induction coil is optimal for one strip material of one thickness.

- ***Two degrees of freedom (thickness and width)***

  If besides the thickness also the width of the strip is variable, the system can be tuned by changing frequency for the thickness and by shifting the complete coils depending on the strip edges for the width. But the coil head is optimal for one strip thickness only.

- ***All practicable degrees of freedom (thickness, width, material and temperature profile)***

  A system, which provides full freedom in adjusting to the heating task, can be realized, if in addition to the power and frequency of the power supply the inductor sections can be independently adjusted. The two inductor sections in all layers of the inductor will be moved autonomously. Then the installation is able to heat strips of different width, thickness and material in the desired way. The optimal system can be realized for each strip varaiation.

NUMERICAL RESEARCH

For the development of the VABID-system the numerical modelling was used intensively. Only by the help of mathematical tools it was possible to design succesfully such a complicate system. Beside expanded parametrical studying special aspects were also investigated.

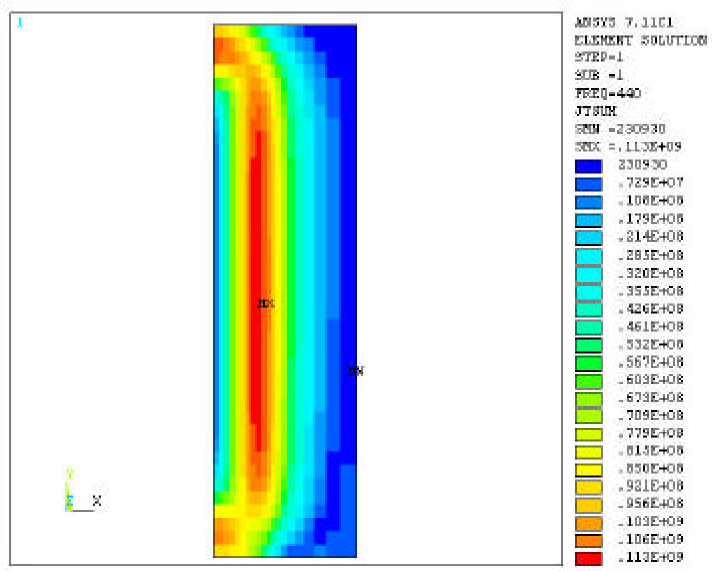

Figure 3. Power density distribution in the strip for a two layer VABID system

One main element of the VABID-concept is the electromagnetic compensation of the connections. How effectively the electromagentic compensation works, is impressive demonstrated in the figure 3. The distribution of power density in the strip is shown for a two layer VABID system. Because of symmetry in the direction of movement, only half of the system is modelled and demonstrated in the figure. The difference between the connection side on the bottom of the figure and the other side on the top is very small.

In order to clarify the influence of the number of inductor layers, a VABID system to heat up an aluminum strip of the thickness 0.5 mm and width 1000 mm for different constellations was simulated. Induction coils with up to four inductor layers have been optimized. For a better comparison the basic conditions were kept similar. The pole pitch and the process data, as for instance the speed of motion and the goal temperature were the same. The pole pitch is an important design parameter for transverse flux heaters. Therefore it was selected equal for all systems as well. In each case the goal of the

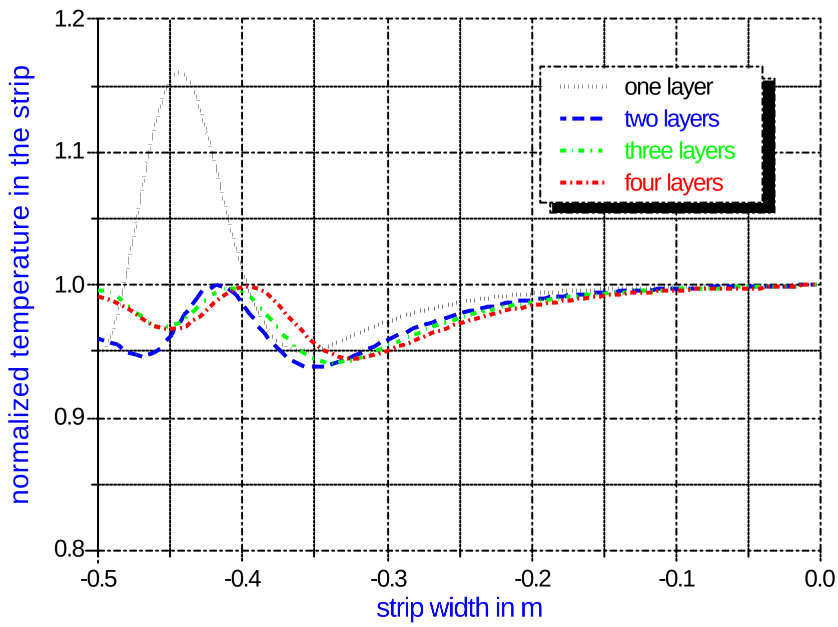

Figure 4. Simulation results for systems with various amount of inductor layers

optimization was a homogeneous output temperature. The results of the optimizations for the different systems in dependence on the number of inductor layers is shown in table 1. The indicated values are the maximum deviations related to the temperature in the middle of the strip. The associated temperature distributions are shown in figure 4. The temperature scale is normalized to the middle strip temperature.

Table 1. Influence from number of inductor layers to the homogeneity of temperature profile for a simplified configuration

number of inductor layers	1	2	3	4
maximum deviation	21.2 %	6.2 %	5.8 %	5.5 %

As the table and the temperature curves illustrate a very good homogeneity can be achieved by the system with only two inductor layers. Any further increase of the number does not bring crucial improvement. Because the fundamental goal of the design is robustness, for the further investigations a system with only two inductor layers was choosen for the experimental prototype.

EXPERIMENATL INVESTIGATIONS

The laboratory set-up was configured for industrial dimensions of strip, induction coil and speed of motion. The main feature of the VABID-system is its flexibility in the strip width. Therefore it has been intensively checked by experimental tests first of all. The measured temperature profiles in different strips are shown in figure 5. The results correspond to aluminium strip of 0.5 mm thickness and width from 600 mm to 1000 mm. They demonstrate the effectiveness of the installation to heat the strip of different width with nearly

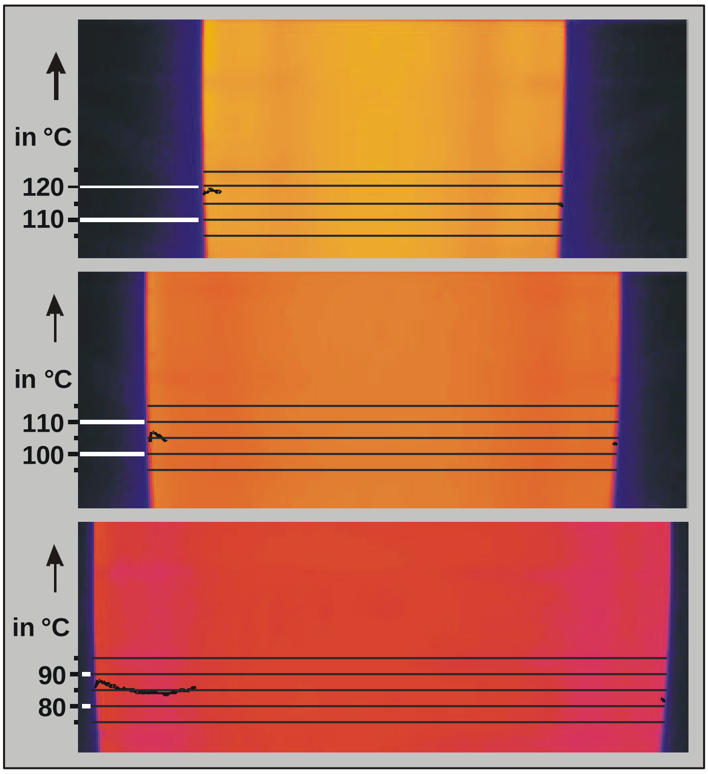

Figure 5. Measured temperature distributions for different strip width of aluminium strip

the same temperature profile. Over the strip width the deviation from the middle temperature is below ± 3.5 % for all three strips.

CONCLUSION

The transverse flux induction heating offers numerous advantages in comparison to conventional heating processes to treat the thin metal strips. It is an innovative method to develop new generation of production lines and products. To have flexible heating installations a new induction coil concept has been developed. It demonstrated high flexibility and effectiveness in numerical and experimental tests.

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Authors:

Dipl.-Ing. Holger Schülbe
Dr.-Ing. Alexander Nikanorov
Prof. Dr.-Ing. Bernard Nacke

all:
Institute for Electrothermal Processes, University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hannover, Germany
Phone: +49 511 762 3928/2872
Fax: +49 511 762 3275
E-mail: schuelbe@ewh.uni-hannover.de