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Numerical simulation and investigation of induction through-heaters in dynamic operation mode

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Abstract

Purpose – Because of their widespread use in industry, induction through-heaters of various metal products must be of high effectiveness not only in "quasi" steady-state operation but in different transient modes as well. Nowadays, they are usually designed to provide the required characteristics in "quasi" steady-state operation mode mainly. The purpose of this paper is to examine numerical simulation of transient processes in induction through-heating lines generally and investigate dynamic temperature fields during the first start of the heaters particularly.

Design/methodology/approach – The research methodology is based on coupled numerical electromagnetic and thermal analyses using FEM approach. ANSYS simulations are supported with the developed tools for imitation of mass transfer effects in continuous induction heating lines.

Findings – The results show that transient temperature fields in the heated strip or slab significantly differ from their "quasi" steady-state descriptions. Local temperature variations acquired in longitudinal as well as transverse flux induction heaters during the first start have been predicted.

Practical implications – The received results can be used for design of induction through-heaters and improvement of their characteristics in dynamic operation modes.

Originality/value – Investigation of dynamic characteristics of the heaters in dynamic modes can be only done by numerical modelling based on special algorithms providing a time loop additional to coupling between electromagnetic and thermal analyses. Such algorithms have been developed and used for investigation of two types of induction installations: through-heaters of cylindrical billets for forging and heating lines of strip or thin slab for rolling mills.

Keywords Induction heating, Strip, Slab, Dynamic mode, Numerical simulation, Heat transfer, Electromagnetism

Paper type Research paper

Introduction

Induction through-heaters of various metal products are wide spread used in industry because of their ability to be directly built into technological lines. Because of this, the through-heaters must be of high effectiveness not only in "quasi" steady-state operation but in different transient modes as well. Induction through-heaters are usually designed to provide the required characteristics in "quasi" steady-state operation mode mainly. Nevertheless, in industrial practice, regime of the heater can be under changing more than a half of total operation time. Transient processes, caused by controlled change of technological conditions and uncontrolled disturbances in the line operation, play significant role in effectiveness and quality of the heating.

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Investigation of dynamic characteristics of the heaters in dynamic modes can be only done by numerical modelling. To simulate different kinds of transient modes in induction heating systems, a special group of numerical models is required to be developed. The models must simulate the heating process distributed not only in space but in time as well. That is why transient models of induction through-heating should be based on special algorithms providing a time loop additionally to coupling between electromagnetic and thermal analysis. An important feature of such algorithms is also a necessity to simulate the heating process in a line consisting of several inductors installed one after another.

Such numerical models have been developed and used for investigation of dynamic modes for two types of induction installations: through-heaters of cylindrical billets for forging and heating line of strip or thin slab for rolling mills.

Through-heaters of cylindrical billets for forging

Induction through-heaters for forging are usually designed to provide the required characteristics in so-called "quasi" steady-state mode where temperature field in the heater is constant or it is periodically changed with step-by-step movement of the workpiece. Optimization of heater operation in "quasi" steady-state mode is usually realized on the design phase. Thus, numerical models of induction through-heating process only in "quasi" steady-state operation mode were required (Börgerding and Mühlbauer, 1997).

However, in industrial practice, the induction through-heaters operate under various controlled and uncontrolled disturbances. The heater regime can be under changing more than a half of total operation time. Transients caused because of controlled excitations include the system reaction on initial start of the heater, restart after technological brake, changing the workpiece specification or production rate of the installation. Reaction of the heater on uncontrolled disturbances leads to more or less slight continuous transients. Special group of numerical models is required to simulate different kinds of transient modes in induction heating systems. In these models, the thermal analysis must include time additionally to one, two or three space coordinates. Of course, transient modelling of induction through-heating should be based on special algorithm which provides coupling between electromagnetic and thermal analysis.

One 2D transient numerical model of induction through-heater for cylindrical billets with continuous movement has been developed according to an algorithm shown in Figure 1. For numerical simulation, the continuously running physical heating process is replaced by big enough number of time steps. Electromagnetic and thermal analysis are carried out at each time step of simulation. The Joule heat distribution in the workpiece, calculated in the electromagnetic analysis, is used as an excitation for the thermal one at the running time step. Temperature-dependent electro-physical material properties are corrected for electromagnetic analysis at the running time step according to temperature distribution in the workpiece after the previous time step. Thermal analysis includes simulation of thermal losses by convection and radiation from all open surfaces of the calculated system. Heat flux by radiation is calculated taking into account view angles. Input of voltage or current of the induction coil is individually input in electromagnetic analysis at each time step. This approach allows simulating various kinds of transient modes. The "quasi" steady-state operation mode of the heater can be calculated as well via transient one after long enough time. The model is realized

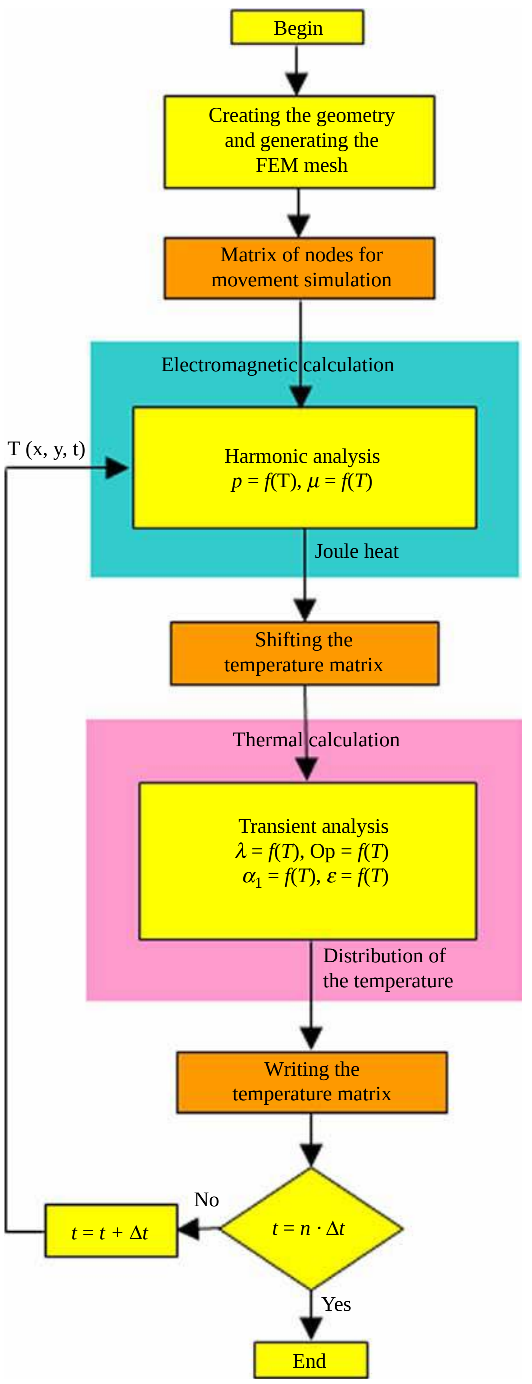

Figure 1.
The algorithm for coupling of electromagnetic and thermal analysis in transient modes with the workpiece movement

using finite element method on the basis of commercial program package ANSYS. It can be used for simulation of induction through-heaters of various designs together with different control systems.

One robust way to implement movement of the workpiece is based on shifting the temperature field before each time step of thermal analysis (Galunin *et al.*, 2008). This approach can be only applied for induction heating systems with continuous movement of endless workpiece of constant cross-section. This approach is very effective but it requires uniform numerical mesh in the workpiece in the direction of motion. Speed of the workpiece is taken into account via value of time step.

The described model has been successfully applied for numerical investigation of several induction heating systems. One example of the simulated induction through-heater for forging is shown in Figure 2. An endless cylindrical steel workpiece with diameter of 34 mm is heated in one solenoid induction coil of 37 windings with length of 1.4 m. Speed of the workpiece motion is of 2 m/min. As it is typically made in induction heaters for forging, the coil is casted into the refractory for better thermal insulation and protection of the coil windings. Numerical mesh in the workpiece is uniform in the direction of motion.

The modelled heater has been tested in transient as well as in “quasi” steady-state operation modes. Temperature field in the workpiece and refractory in the “quasi” steady-state mode is shown in Figure 3. This regime has been reached with constant current in the coil.

The modelled heater has been investigated during its first start from cold workpiece and refractory. Dynamics of the surface temperature distribution along the workpiece is shown in Figure 4. One can see that the transient mode after the first start of the heater is finished inside the inductor after 80 time steps. All electrical data of the heater during its transient operation are available as well.

Temperature distributions at the surface and in the centre of the workpiece in the reached “quasi” steady-state mode are shown in Figure 5. The results, received using the developed model, have been confirmed by comparison with numerical simulation using the model for steady-state mode only.

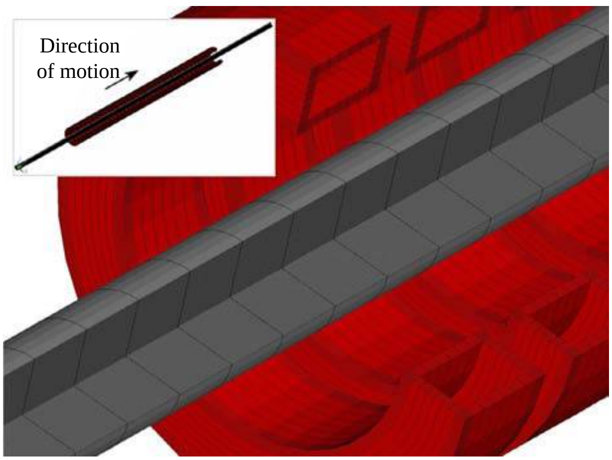

Figure 2.
Geometry and FEM mesh of induction coil and workpiece in the simulated through-heater for forging

Through-heaters of strip or thin slab for rolling mills

Strip or thin slab casting lines with rolling mills are nowadays under active development (www.steel-n.com/esales/general/us/catalog/minimill/). The thin strip is cooled down very fast because of high thermal losses. Additional reheating of strip or thin slab is needed before final rolling. Compared to thick slab casting lines it is extremely non-effective and in most cases even impossible to use gas fired furnaces in strip or thin slab casting lines. Only induction installations can realize the needed fast heating of the strip with good energy efficiency. However, induction heating lines need not only an optimal design oriented to "quasi" steady-state mode but also effective control in dynamic modes.

Induction heating lines for rolling mills are of extremely high power. Typically, they consist of numerous inductors located between the transporting rolls one after another like it is shown in Figure 5. Even small improvements in the design and operating

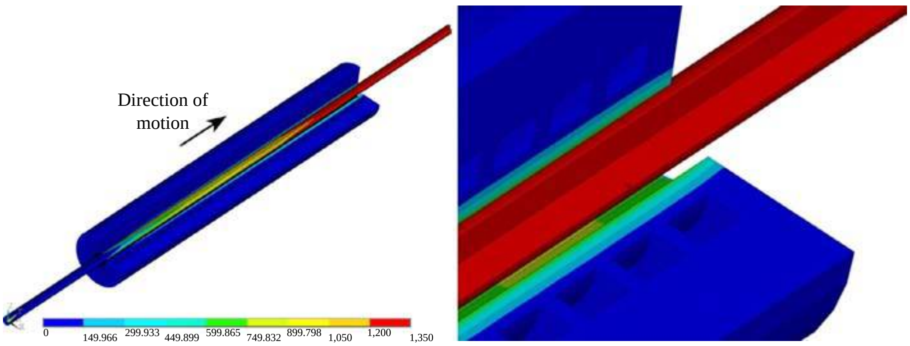

Figure 3.
Temperature field in the workpiece and refractory in "quasi" steady-state mode

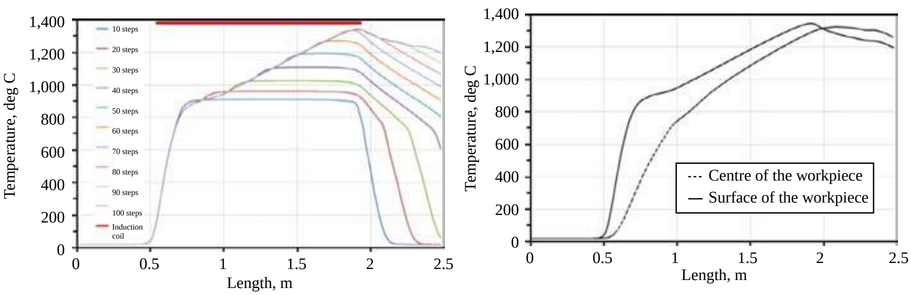

Figure 4.
Temperature distribution along the workpiece during the first start of the heater and temperature distributions at the surface and in the centre of the workpiece in "quasi" steady-state mode

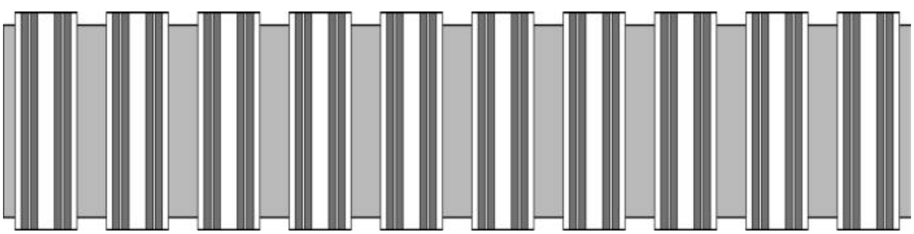

Figure 5.
Typical structure of induction heating line for rolling mills with ten inductors

modes of such big lines have significant technical and economical effects. Induction heating lines for rolling mills can be based on either longitudinal or transverse flux induction systems (Zlobina *et al.*, 2001). They are very close in behaviour in "quasi" steady-state operation mode, but their dynamic characteristics are rather different. Only numerical simulation can solve the problem of dynamic behaviour of electromagnetic and thermal processes in induction heating lines.

Numerical models for simulation of induction through-heating process in dynamic operation modes have significant features compared to traditional models for "quasi" steady-state mode. Of course, they have to include coupled electromagnetic and thermal analysis taking into account the workpiece movement. Additionally, very often these models should consider the system geometry changed in time. Such task, especially for 3D simulation, required development of very stable simulation algorithm shown in Figure 6. As usually, continuously running physical heating process is replaced by big enough amount of time steps. At each time step, the system geometry is assumed of no change.

The first part of the algorithm includes creating all electromagnetic and thermal environments needed in the second part of the algorithm. The created environments are saved in form of database and have all necessary for solution records like system geometry, numerical mesh and boundary conditions. The electromagnetic environments are only open for actual temperature distribution for correction of material properties and for excitations in form of induction coil current or voltage. The thermal environments read initial temperature distribution from the previous time step and distribution of power density coming from the electromagnetic analysis.

The second part of the algorithm starts from a set of electromagnetic and thermal calculations at each time step of the heating process in the first inductor. Then, this procedure is repeated for the heating process in the next induction coil. All results of electromagnetic and thermal calculations are saved at the end of each time step.

The developed algorithm is realized in commercial program package ANSYS based on finite element method. Electromagnetic analysis is carried out in harmonic statement with temperature-dependent material properties. Structure of the algorithm allows simulating longitudinal as well as transverse flux induction systems or their combination. The thermal system includes the heated strip and refractory of the inductor with radiation exchange between their surfaces. The thermal system can be extended if necessary. Numerical mesh is optimized to reach a compromise between good calculation accuracy and acceptable runtime of the model.

Longitudinal flux through-heaters of strip or thin slab

Induction installations for heating of strip or thin slab are wide spread in industry because of their numerous advantages against gas fired furnaces. Mainly, they are based on longitudinal flux concept which provides robust and stable generation of energy in the strip with uniform distribution over the strip width. Electromagnetic edge effect in the strip can be significant in case of thick slab only.

As an example, one induction heating line consisted of ten longitudinal flux coils running with frequency of 20 kHz has been numerically investigated in their dynamic operation modes. Steel strip with width of 1,200 mm and thickness of 10 mm is reheated from starting uniform temperature of 900°C before final rolling. Beginning of the strip goes through all running induction coils like it is shown in Figure 7. Each coil has fore

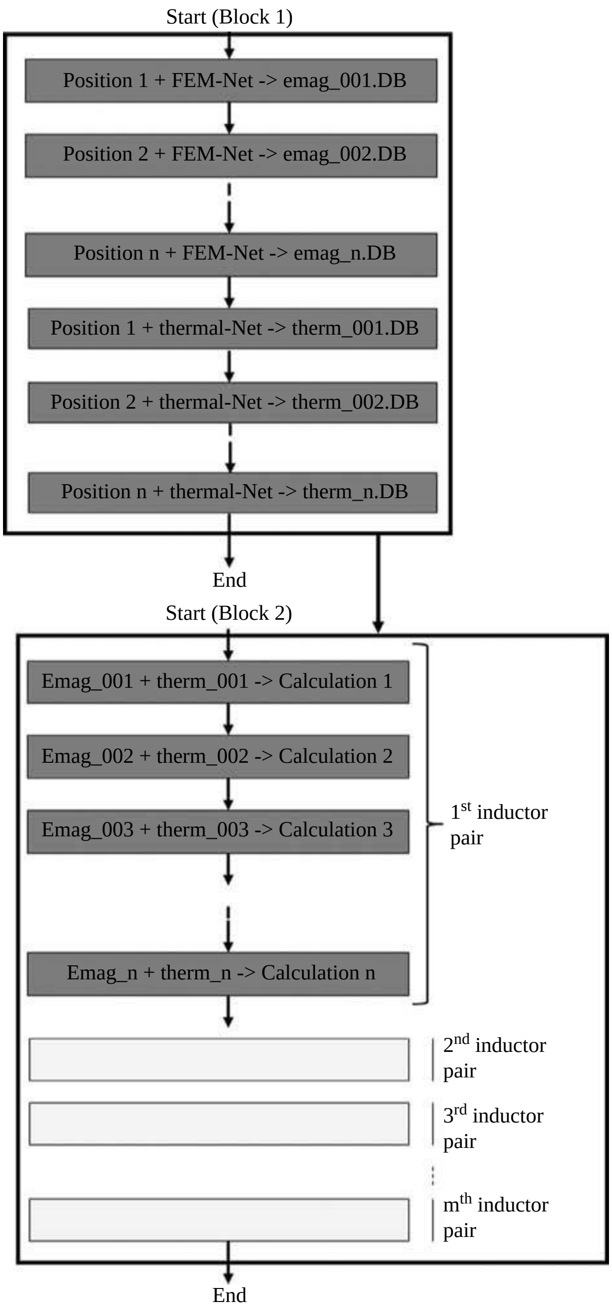

Figure 6.
Algorithm for numerical simulation of dynamic modes in multi-coil induction heating lines

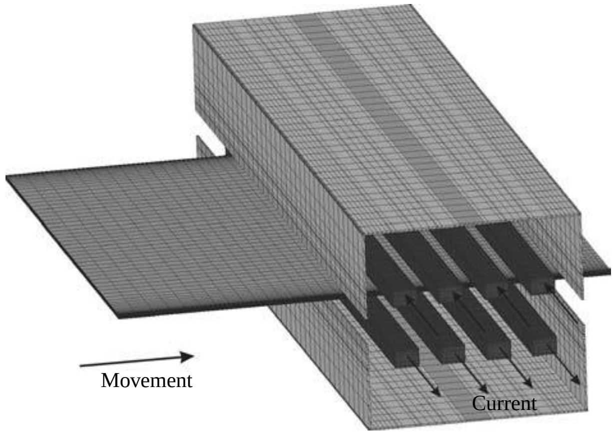

Figure 7.
3D model of longitudinal flux induction system

windings covered by electromagnetic screen made of copper plates. The coil is accomplished by refractory for better thermal insulation (Figure 8). Thermal losses by radiation from the surface of the strip and refractory are calculated according to 3D view angles. Convective losses are included into the model as well in spite of their small impact to the heat exchange process.

The processes at the beginning of the strip with length of one induction coil heating zone have been simulated in the example presented. Qualitative temperature field at the beginning of the strip is shown in Figure 9. As it was expected, temperature profile over the strip width is mostly homogeneous except the strip edges which are colder on

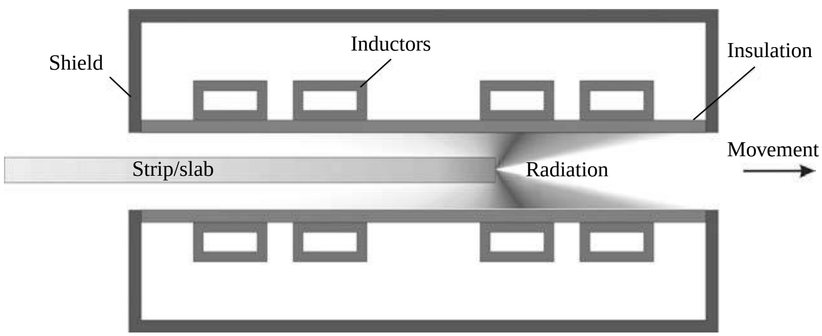

Figure 8.
3D radiation losses from the strip surface

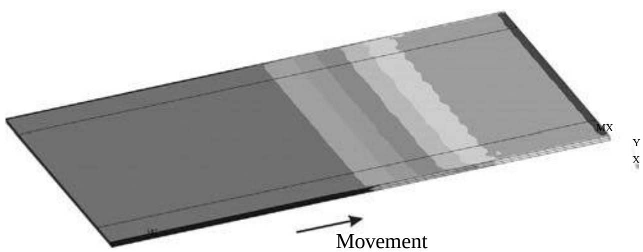

Figure 9.
Temperature field at the beginning of the strip in case of longitudinal flux heating

around 100 K because of bigger thermal losses. At the beginning of the strip, one can see a zone of 20 mm with around 70 K higher temperature while an opposite effect could be expected because of higher thermal losses from the strip beginning (Figure 10). It shows that even longitudinal flux heating concept gives 3D effects in temperature field at least in the beginning of the strip.

Transverse flux through-heaters of strip or thin slab

Induction heating of strip or thin slab can be done using transverse flux concept, which provides several advantages against longitudinal one especially for thinner products. First of all, high electrical efficiency can be reached with much lower frequency. Big potential to control temperature profile over the strip width is the second advantage of the transverse flux concept. This advantage is of high importance for induction heaters for rolling mills where even inlet temperature profile is very far from homogeneous one.

One example of numerical investigation of dynamic modes for the heating line described above is presented in case of transverse flux inductors (Figure 11). The heaters operate with frequency of 1 kHz. Qualitative temperature field at the beginning of the strip is shown in Figure 12. Temperature profile over the strip width with overheated edges is typical for transverse flux approach without special optimization of the coil heads (Figure 13 left). It is one of very powerful methods to control temperature profile over the strip width.

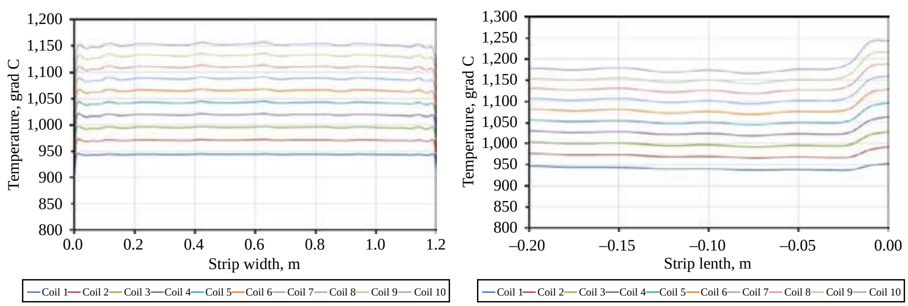

Figure 10. Temperature profiles over the strip width and length after each longitudinal flux coil

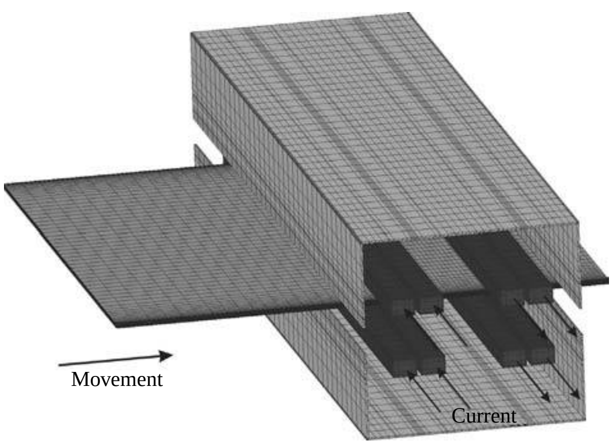

Figure 11. 3D model of transverse flux induction system

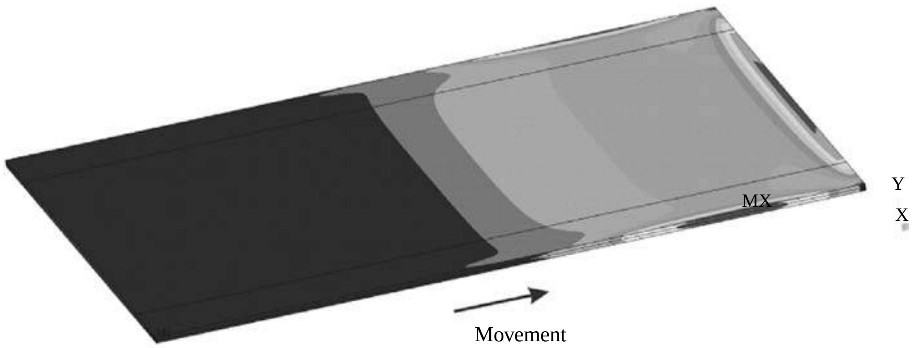

Figure 12.
Temperature field at the beginning of the strip in case of transverse flux heating

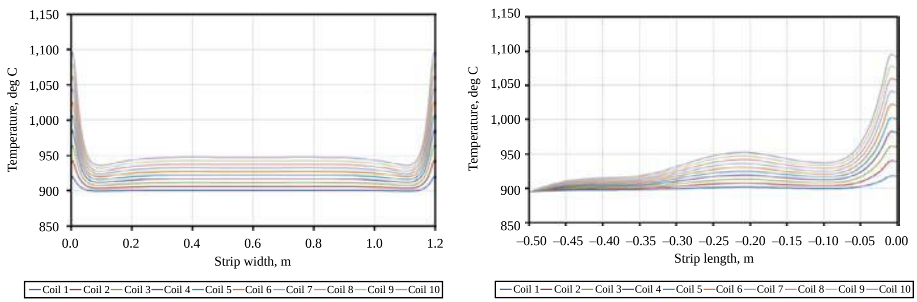

Figure 13.
Temperature profiles over the strip width and length after each transverse flux coil

Behaviour of temperature field at the beginning of the strip is completely different from the longitudinal flux heating. One can see a zone of around 50 mm where temperature grows dramatically (Figure 13 right). This effect is much stronger than in case of longitudinal flux heating. At the same time, the corners at the beginning of the strip are not heated at all and, therefore, temperature drop in there can be very big.

Conclusions

Dynamic operation modes play significant role in forming main characteristics of induction through-heaters. Dynamic behaviour of the heaters can be investigated and optimized by numerical modelling only. Several approaches have been developed and applied for simulation of different dynamic regimes of induction through-heaters. Numerical models and results of investigated for the first start of through-heaters for forging and rolling mills have been presented. Significant difference of dynamic behaviour between longitudinal and transverse flux induction heaters of strip or thin slab has been detected. The received results can be used for design of induction through-heaters and improvement of their characteristics in dynamic operation modes.

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