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Detailed 3-D numerical investigation of continuous longitudinal flux heating for thin strips

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Abstract

Most of the studies on longitudinal flux heating (LFH) deal with special applications and a strip thickness above 15 mm. The aim of this paper is to present the dependence of different geometric parameters for thinner strips. The influence on the temperature distribution and the efficiency will be systematically analyzed. The length, width and the air gap of the induction coil are subjects of the investigation. For the study a 3D numerical model is used.

Key words: Induction, longitudinal flux heating, strip heating, numerical simulation

Introduction

The industry has a big demand on efficient and flexible heat processing of metal strips. Therefore the LFH becomes more and more interesting in comparison to the conventional heating. It is important to have a deep knowledge of the process, because a homogenous temperature distribution is not always given and various things have to be observed. In past studies different aspects of LFH have been examined. In [1] the edge effects and end effects were investigated. The industrial application of LFH was studied in [2] with the main view on slabs with a thickness of 16 mm and width of 1550 mm.

The paper [3] presents the influence of the slab geometry of the temperature distribution and a comparison between LFH and transversal flux heating. All named studies refer to plate thicknesses over 10 mm. The nonlinearity of the ferromagnetic property of steel was discussed in [4] for strips with a thickness under 10 mm.

The numerical model

For the numerical modeling and calculation the commercial software package ANSYS 16 was used, which bases on the finite-element-method (FEM). The calculation algorithm which is used in this study is divided in two sub-steps. In each iteration step a harmonic electromagnetic and a transient thermal calculation is performed. To solve the Maxwell Equation's for the harmonic electromagnetic field the magnetic vector potential is used. The result of this solution is the heat sources distribution in the work piece. In the second sub-step the heat transfer equation is solved for a time interval Δt regarding thermal losses due to radiation and convection. The solution of the electromagnetic calculation is the input value for the heat transfer equation. The output value is the temperature distribution. In the next iteration step the temperature distribution is the input value for the harmonic electromagnetic calculation. The material properties specific electrical conductivity, relative permeability, specific thermal conductivity and the specific heat capacity are adjusted on the new temperature distribution. To realize the moving of the metal strip an algorithm is used, which was developed at the Institute of Electrotechnology. In order to shorten the computation time, the geometry is not shifted, because this would mean to mesh the geometry in every iteration step. The temperature distribution is stored in a matrix and in each new iteration step the temperature is written to the next node.

For the calculation of the following results a 3-dimensional model is used. Because of symmetry only the half of the system is modeled to reduced the calculation time. The influence of the slope of the induction coil on the electromagnetic and thermal values is not considered. The induction coil has a rectangle cross section. For an exact calculation it is important to mesh the edges of the strip very fine. The calculations are based on the material properties of C45E steel [5]. The reference thickness of the strip is 1 mm, because in many industrial application strips with a thickness in this range are used. The frequency is 38.5 kHz. The width of one winding is 30 mm and the distance between the windings is 8 mm to 10 mm.

Influence of the length of the induction coil on the temperature distribution and the efficiency

The length of the induction coil is an essential factor, because it influences the homogeneity of the temperature distribution. Is there not enough space for the required induction coil length there are other possibilities to take influence on temperature distribution. The length of the induction coil will be varied from 150 mm to 600 mm. The air

gap is 40 mm. To ensure the comparability of the results, the power is kept constant in the metal strip by adjusting the current this means the temperature level is constant, too.

Fig. 1 shows the temperature distribution from the middle of the strip to the edge of the strip. The four graphs have the same qualitative behavior. With increasing distance from the center of the strip to around 50 mm to the edge the temperature drops down, then the temperature rises to a maximum in 10 mm to the edge and then fall down again. The first drop results in a lower current density in this area. The overheating can be explained as follows: On the one hand the proximity effect works. It means that the currents in the induction coil and in the strip with opposite directions flow as close as possible. Then the inductance of the system is minimal. On the other hand the current in the strip wants to take the shortest way to reduce the electrical resistance. On the basis of these two effects the current is compressed and this results in a high current density. The second drop appears because most of the current does not flow to the edge of the strip.

The dependence of the length of the induction coil results in the same qualitative behavior but in different quantitative temperature distribution. With increasing of the length of the induction coil the temperature distribution becomes more homogeneous. Tab. 1 presents the percentage difference between the minimum and maximum temperatures.

Induction coil length [mm]	150	300	450	600
Difference	0,146	0,102	0,076	0,073

Tab. 1: Temperature difference in the dependence of the induction coil length

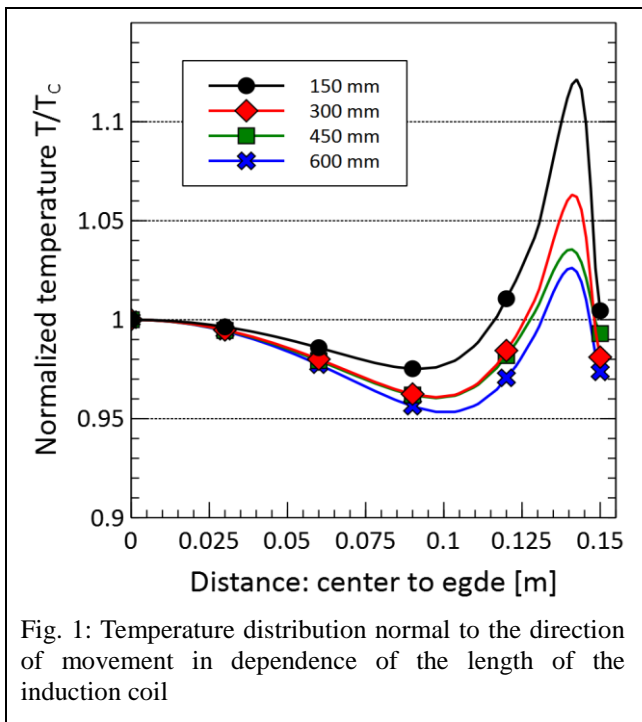


Fig. 1: Temperature distribution normal to the direction of movement in dependence of the length of the induction coil

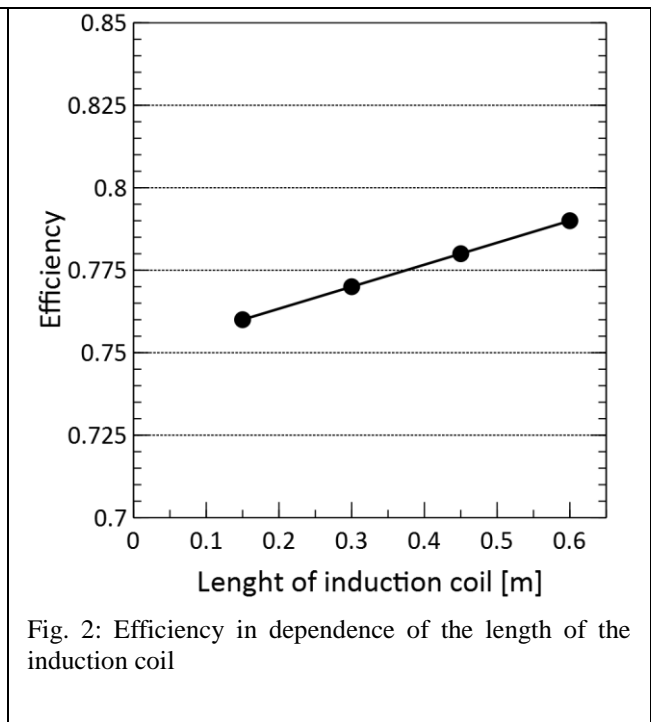


Fig. 2: Efficiency in dependence of the length of the induction coil

The efficiency depends on the length of the induction coil (see Fig. 2) and increases with a longer coil. The current for a 150 mm long induction coil (4 turns) is 1300 A and for a 600 mm long induction coil (16 turns) is 520 A. The electrical resistance increases with the length of the coil. The resistance for 16 turns is approximately 4 times greater than for 4 turns. On the other hand a lower current in the induction coil is required for 16 turns. In an ideal case with a coupling factor of 1.0 the current for the longer coil has to be divided by 2. That means a current of 650 A in a 16 turn coil generates the same power in the induction coil and the work piece as a current of 1300 A in a 4 turn coil.

In other words, to cause the same power in the work piece and the coil (600 mm) the magnetic field intensity has to be two times smaller. In the numerical calculation the current is smaller than 650 A. That means the part of the magnetic stray field is smaller and the coupling factor is greater than for a short induction coil.

The 3-dimensional power density distribution in the strip is pictured in Fig. 3 and Fig. 4 for two different lengths. The power density distribution is not symmetrical because the moving strip at the end of the induction coil has a higher temperature than at the beginning. As a consequence of this the specific electrical conductivity at the end of the coil is higher which results in different power losses.

A comparison of the temperature curves with the power density is in a good agreement, because heat conduction plays in continuous heating processes a minor role, if the velocity of the strip is high enough. But at the edge of the strip is a big difference of the power density distribution in a small area. In this area the temperature distribution is smoother than the power density distribution. Because of a big gradient in this area thermal conduction works to equalize the temperature.

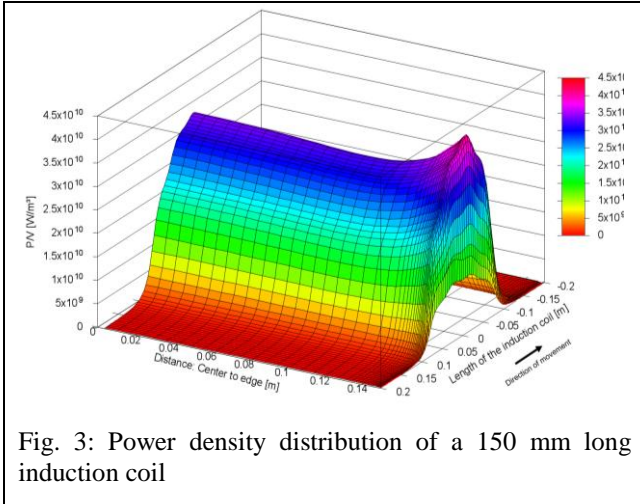


Fig. 3: Power density distribution of a 150 mm long induction coil

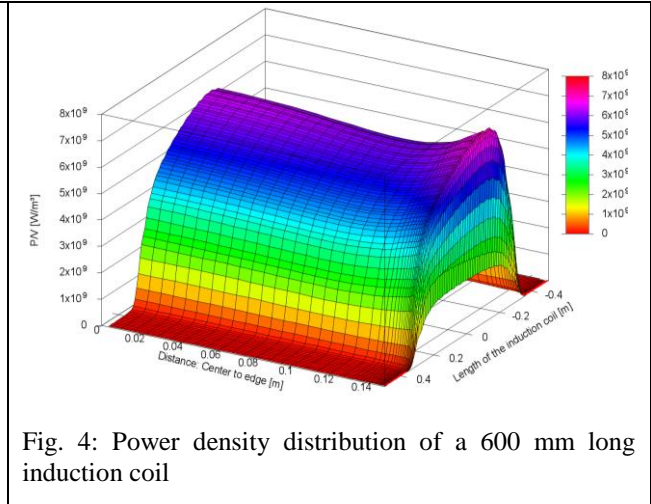


Fig. 4: Power density distribution of a 600 mm long induction coil

Influence of the distance between the induction coil normal to the strip on the temperature distribution and the efficiency

Another important geometric parameter is the air gap copper to copper normal to the strip surface, because the coupling between induction coil and the strip is influenced. In order to investigate the influence to the temperature profile the air gap is varied among 10 mm to 120 mm. The length of the induction coil (600 mm) and the width (half model 150 mm) of the strip are constant. The power in the strip is kept constant by adjusting the current.

The influence of the air gap on the temperature is shown in Fig. 5. An increasing of the air gap results in a more homogeneous temperature distribution and undercooled edges. A smaller air gap results in an undercooled area between 0.025 m to 0.125 m from the strip center and an overheated edge. With a bigger air gap the Proximity-Effect has not so much influence of the current.

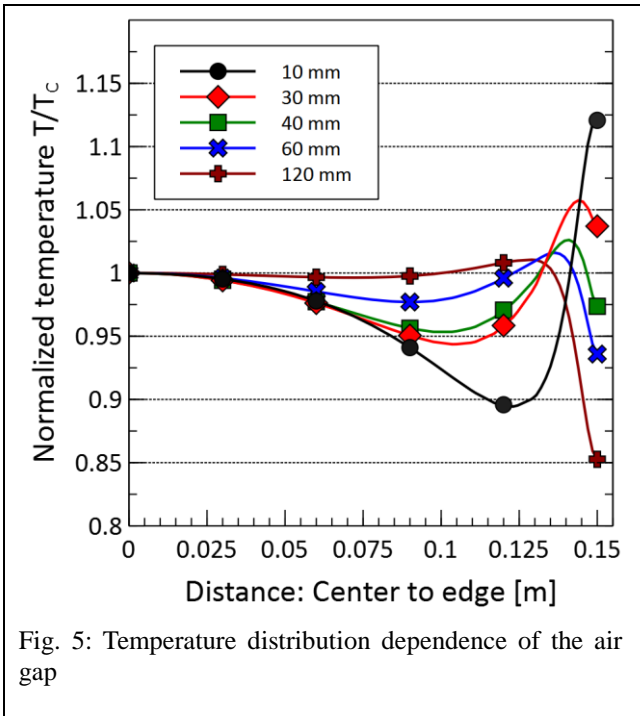


Fig. 5: Temperature distribution dependence of the air gap

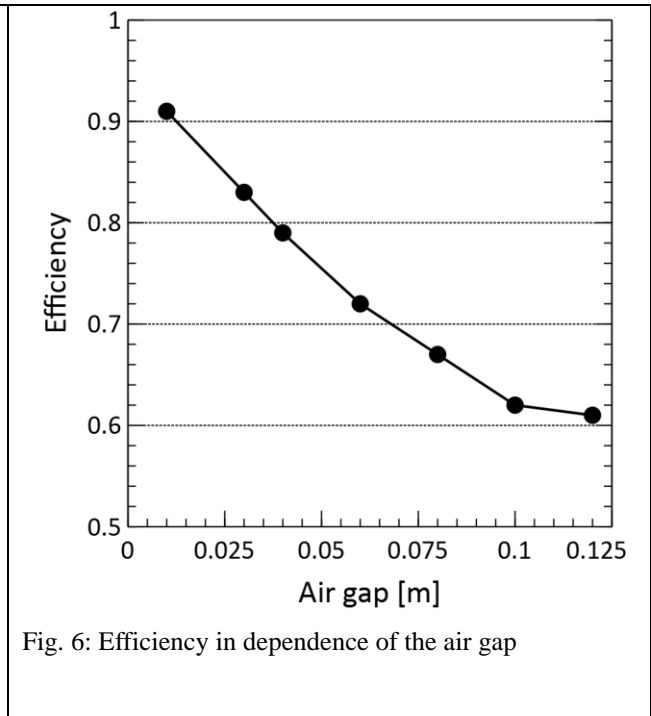


Fig. 6: Efficiency in dependence of the air gap

The efficiency (see Fig. 6) falls with a larger air gap because the magnetic stray field is bigger. That means a smaller part of the magnetic field is coupled with the strip.

The advantage of a large air gap is the more homogenous temperature distribution in the middle part of the strip but the edges are undercooled and the efficiency falls. As a solution for the undercooled edges magnetic flux concentrators can be used.

Influence of the width of the induction coil and the strip on the temperature distribution and the efficiency

The length of the induction coil (600 mm) and the air gap (40 mm) are fixed. The end temperature is in every calculation the same. The width of the strip and the coil are varied. A smaller ratio of width to length results in undercooled edges (see Fig. 7). With the increasing of the ratio the curves change their shapes and a temperature maximum arises.

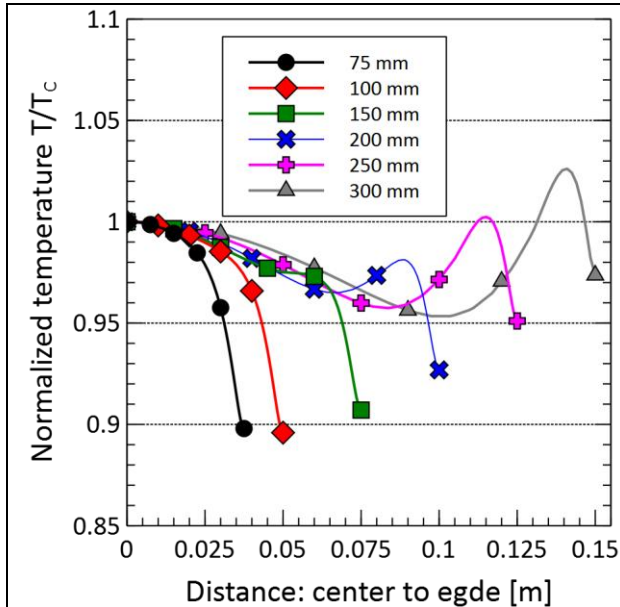


Fig. 7: Temperature distribution in dependence of the width of the induction coil

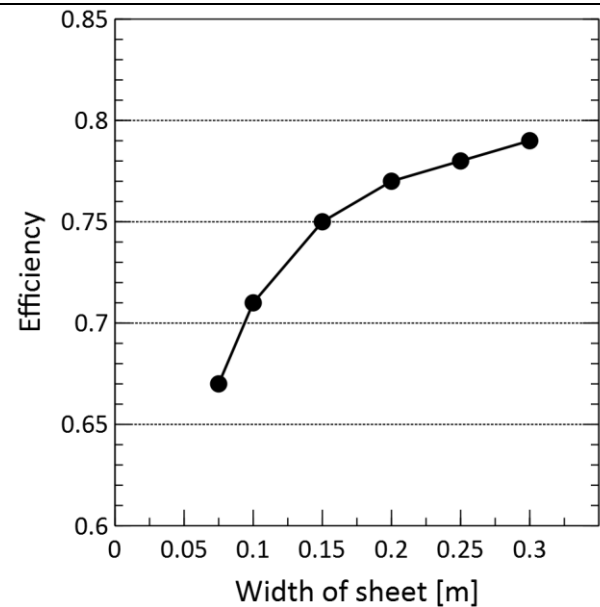


Fig. 8: Efficiency in dependence of the width of the induction coil

The efficiency increases (see Fig. 8) with a bigger ratio (width to length). The significant change of the efficiency has its reason in the power losses of the induction coil. Generally at the corners of the induction coil the power losses are higher as in the straight parts. If the straight part becomes bigger the power losses in the corners are relative smaller to the whole losses in the induction coil.

Conclusion

A 3-dimensional numerical model with a coupled electromagnetic and thermal calculation for LFH was developed. The moving of the strip was realized by shifting the node temperatures. The dependence of changing geometry parameters on the temperature distribution and on the efficiency was showed for different cases. A longer induction coil and a bigger air gap result in a more homogenous temperature distribution. With a longer induction coil the efficiency increases, with a larger airgap the efficiency decreases. Furthermore the ratio of length to width was investigated. The efficiency arises with a wider induction coil.

In further investigations the numerical model should be expanded to a full 3D model so that the slope between the winding can be considered. Afterwards the numerical results should be verified by experiments.

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