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# Numerical Investigation of Transverse-Flux Induction Heating of Ferromagnetic Strip

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## Abstract

Ferromagnetic strip is a material which can be effectively heated up by transverse flux induction. For numerical simulation the most important and necessary material properties of ferromagnetic strip are the resistivity and the relative permeability. This paper deals with the influence of the relative permeability to Transverse-Flux Induction Heating (TFH) of ferromagnetic strip.

## Introduction

The electrical resistivity is a temperature-dependent, more known and easier measurable material property than the relative permeability. Those one is on the one hand depending on the temperature and on the other hand on the magnetic field intensity. The volume magnetic susceptibility $\chi_v$ is equal to the relative permeability minus one and is the coefficient between the magnetization of the material and the magnetic field intensity.

The induction heating by transverse flux has a lot of advantages like the heating over the Curie point. One concept of using TFH is a variable band width inductor, developed at the Institute of Electrotechnology in Hannover, which can be easily adjusted to heat different materials of different width with a customized heating profile.

## 1. Description of the Inductor System and the Numerical Models

The concept of a variable band width inductor (VABID) is shown in Fig. 1. The advantage of the two-layer-system is to adjust the inductor-head and the resulting current density on the strip edge for an optimal temperature distribution.

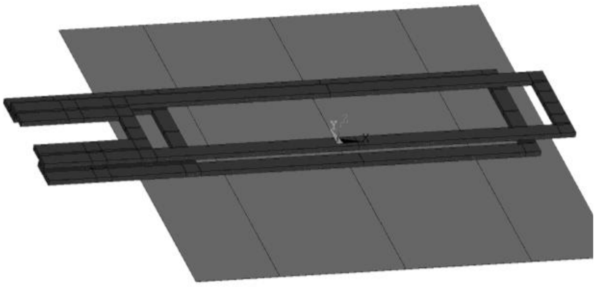

Fig. 1. Design of the VABID-Inductor

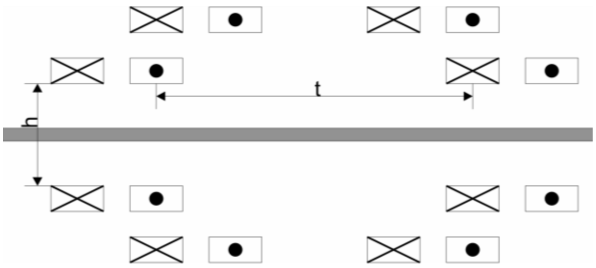

Fig. 2. Direction of the current in the coil

In Fig. 2 the direction of current in the coil is shown. This special connection compensates the electric field near to the connections. Important geometrical parameters of transverse inductors are the air gap *h*, which represents the distance between the top and bottom copper and the pole pitch *t*, which represents the distance between the left and the right conductor. For the investigation of the influence of the relative permeability on the electrical efficiency and the Joule heat distribution the VABID-system with one layer was used. The concept of such a system is the same like the two-layer-system, but the disadvantages are the reduced possibilities to adjust the temperature at the strip edge [1].

## 2. Two-dimensional Numerical Model

The numerical model for the first step of optimization is two dimensional, used to get the optimal frequency. For this model a cutting plane in the regular part and middle of the strip is used. It consists of a copper conductor with the dimension of 22 x 11 mm and a conductivity of $5 \cdot 10^7$ S/m. The distance *h* between the top and bottom copper was set to 100 mm, between the left and right side the value of *t* is configured to 250 mm. The strip-thickness is 1 mm with conductivity of $5 \cdot 10^6$ S/m.

### 2.1 Electrical Efficiency

In Fig. 3 the distribution of the electrical efficiency depending on the frequency is shown. The relative permeability $\mu_r$ as a parameter is in a range from 1 till 30, the electrical efficiency rises to a maximum of 77 % till 78 % and this magnitude can be reached at a frequency of nearly 900 Hz for the same geometry. In a small range of plus-minus 300 Hz the efficiency decreases for one per cent. Also when the relative permeability is increasing from 1 to 30 the electrical efficiency decreases by around one per cent at the optimal frequency.

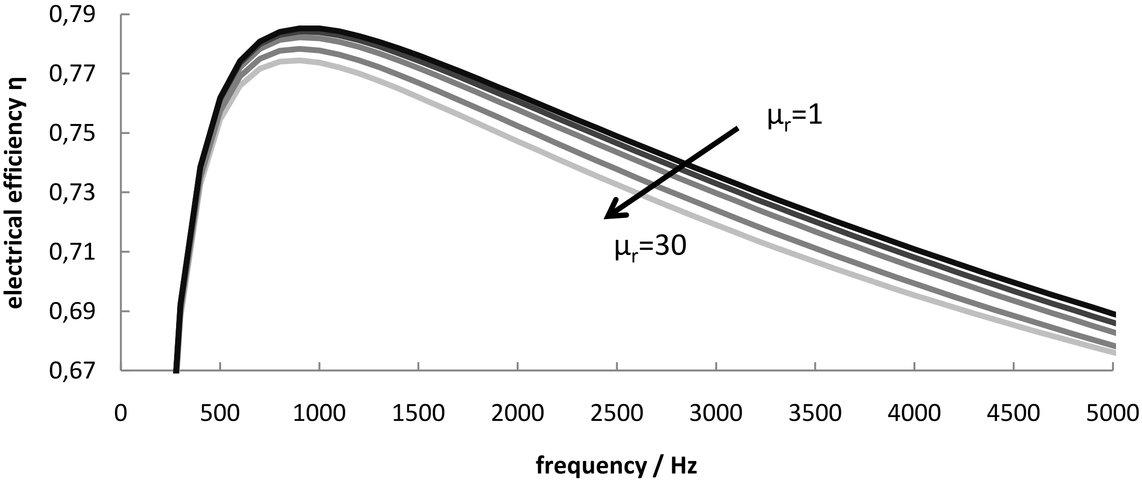

Fig. 3. Distribution of the electrical efficiency for a different relative permeability.

For a frequency of nearly 500 Hz the power factor has his maximum as shown in Fig. 4. With higher frequency or higher permeability the power factor decreases and this is similar to the behaviour of the electrical efficiency.

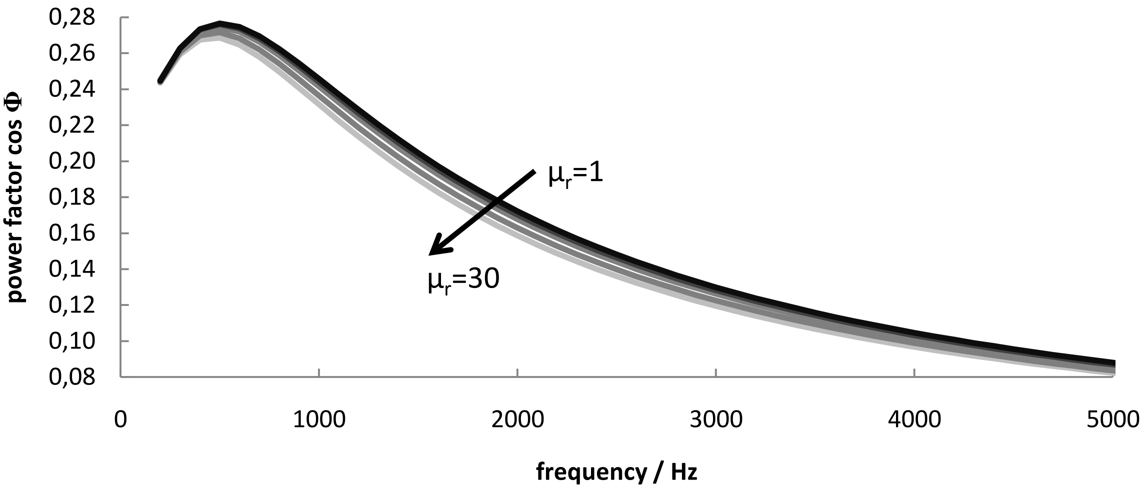

Fig. 4. Distribution of the power factor for a different relative permeability

### *2.2 Electromagnetic Forces*

A total power of 10 kW per meter and an out of center position of 10 mm were used to calculate the force perpendicular to the strip (z-direction). For this electromagnetic force evaluation the *Maxwell stress tensor* (MST) $\boldsymbol{T}$ with the unit vector normal to the surface $\boldsymbol{n}$ was used (2.1).

$$\mathrm{F}_{\mathrm{MST}} = \frac{1}{\mu_0} \int (\boldsymbol{T})\boldsymbol{n} \cdot dz. \tag{2.1}$$

The MST is:

$$T = \begin{bmatrix} T_{11} = B_x^2 - \frac{1}{2}|B|^2 & T_{12} = B_x B_y \\ T_{21} = B_x B_y & T_{22} = B_y^2 - \frac{1}{2}|B|^2 \end{bmatrix}. \tag{2.2}$$

For an asymmetrically position of the strip between the inductors there are two possibilities. On the one hand the forces will increase the out of center position (negative value) and on the other hand the forces will center the strip (positive value).

The electromagnetic force calculated with the MST depending of the permeability and frequency is presented in Fig. 5. For a given permeability of thirty the direction of the force is changing with lower frequency between 300 and 400 Hz. This means that the centering force can change with lower frequency and push the strip to the inductor.

One Part of the force action on the strip is the Lorentz component. Generally the Lorentz force $F_L$ is the multiplication of the electric charge of a particle with the vector cross product from the velocity of a particle and the magnetic flux density. For this case the Lorentz force is equal (2.3).

$$\mathrm{F}_{\mathrm{L}} = \int (\boldsymbol{J} \times \boldsymbol{B}) \cdot dV. \tag{2.3}$$

Solving (2.3) for a harmonic current one part of the Lorentz force is constant and the second part is a harmonic with double frequency [2, 3]. The z-component of this force is always positive and centers the strip between the inductor. The direction of the force is independent of the frequency and permeability, only the value increases with higher ones as shown in Fig. 6.

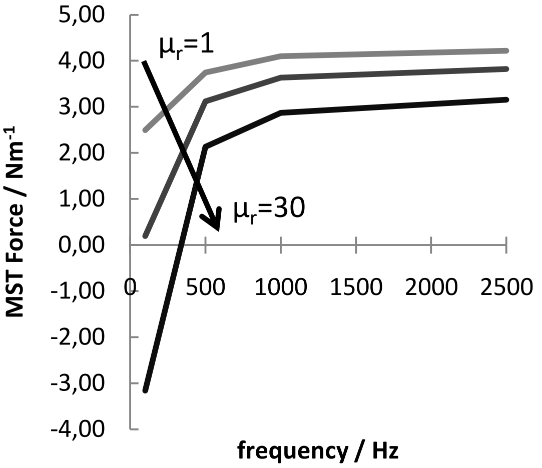

Fig. 5. $F_{MST}$ depending on the permeability and frequency

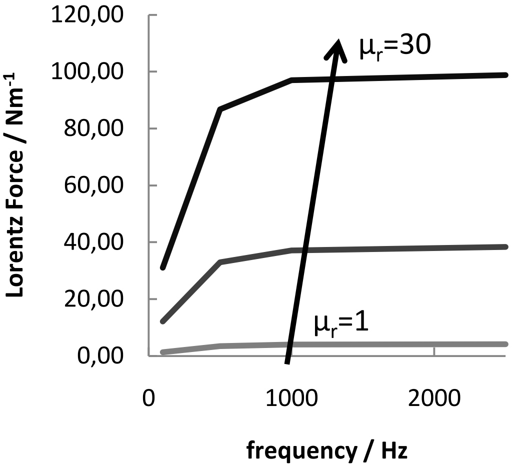

Fig. 6. $F_L$ depending on the permeability and frequency

## 3. Three-dimensional Numerical Model

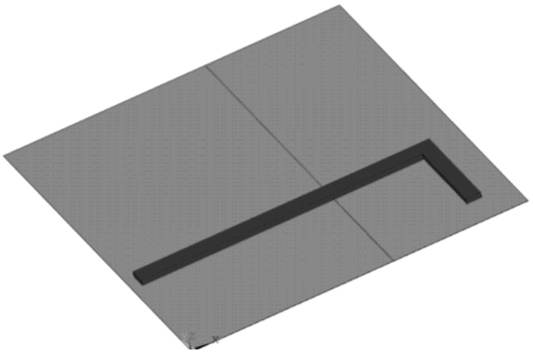

Fig. 7. 3D model of the TFH-system

For a three-dimensional electromagnetic simulation one-eighth of the full geometry, as shown in Fig. 7, was used. In this model no movement of the strip was implemented like in [4]. For this model three simplifications were assumed. At first the middle of the strip thickness is the plane of symmetry, this numerical model has less than half of the elements. The second simplification can be realized by disregarding the connections on the one side. In this step the model was divided in the middle of the strip width. The last step is the plane of symmetry transverse to the strip movement. All in all this model has one-eighth of elements than the full geometry, which reduces the calculation time to suitable times.

### *3.1 Joule Heat Distribution*

The Joule heat distribution, as shown is Fig. 8 for a relative permeability of one, is the result of sum up the elements in alignment with the movement of the strip. This distribution reflects the temperature profile along the strip width without radiation losses, thermal conduction and convection. A typical temperature profile near the inductor head, normalized to the middle of the strip, is an undercooling followed by an overheating.

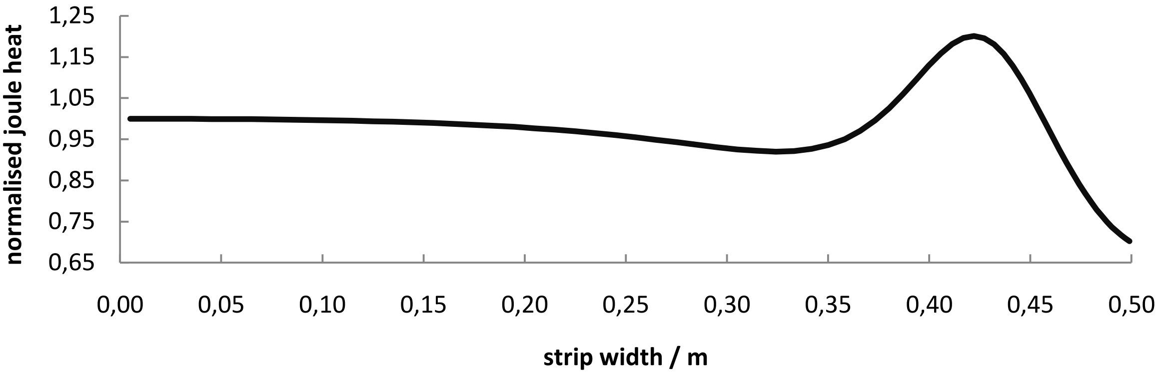

Fig. 8. Joule heat distribution for $\mu_r = 1$

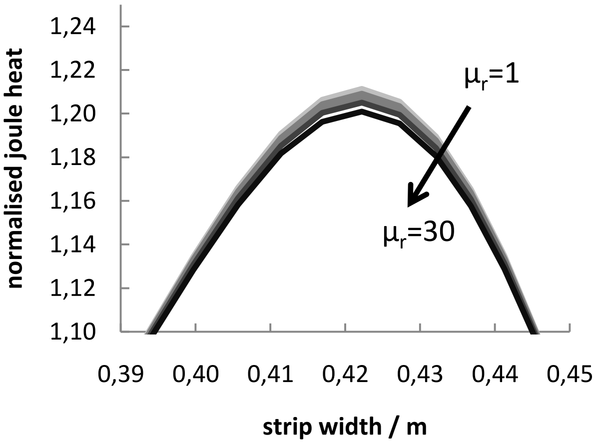

Fig. 9. Joule heat distribution in the position of 390 and 450 mm from the middle of the strip

In Fig. 9 the Joule heat distribution in the position of 390 to 450 mm from the middle of the strip for a different permeability is shown. While in the middle of the strip no influence appears the overheating in the region of the inductor head is different. In this region the Joule heat in the strip induced by this non optimized inductor is around twenty per cent higher than in the middle of the strip. Between a relative permeability of one and thirty the Joule heat decreases by one per cent.

### *3.2 Electromagnetic Forces*

For 10 kW total power and 900 Hz frequency the distribution of the Lorentz force perpendicular to the strip (z-direction) caused from the top inductor was calculated. As already mentioned the Lorentz component has a constant value and a harmonic oscillation [1]. In Fig. 10 the constant value is shown. Between a low and high permeability it is approximately the same distribution.

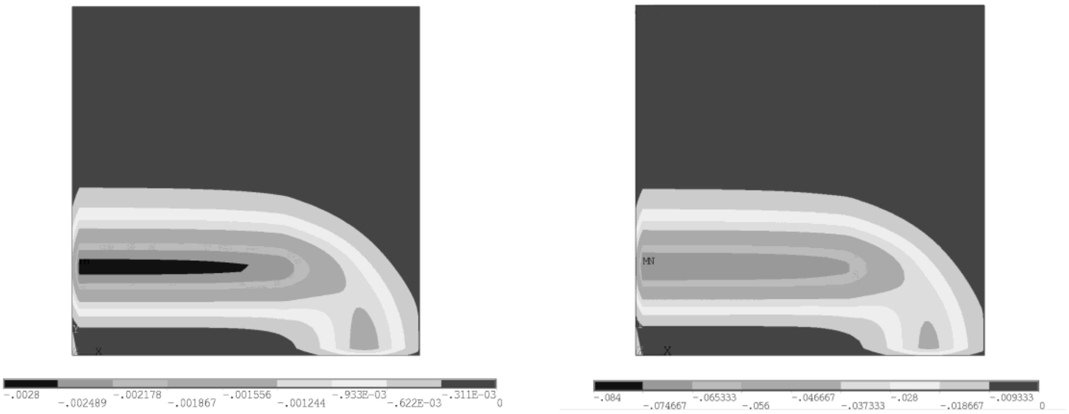

Fig. 10. Z-component of the Lorentz force. $\mu_r = 1$ (left) and $\mu_r = 30$ (right)

The magnitude of the constant and oscillating force action on the strip is demonstrated in Tab. 1. Because the magnitude of the oscillation is less than the constant value, the Lorentz force will center the strip vertically at all times.

One important but not investigated point is the frequency of TFH in the acoustic range. The oscillating component of the Lorentz force evokes noise emissions and directives must be complied.

Tab. 1. Z-component of the electromagnetic forces action on the strip

| | $\mu_r = 1$ | $\mu_r = 5$ | $\mu_r = 10$ | $\mu_r = 20$ | $\mu_r = 30$ |
|---|---|---|---|---|---|
| $F_{L\text{-}Z}$ (con) | 12.5 N | 61.2 N | 122.4 N | 239.0 N | 349.8 N |
| $F_{L\text{-}Z}$ (osz) | 12.3 N | 61.1 N | 120.9 N | 236.3 N | 346.5 N |

## Conclusions

During heating by transverse flux it is not possible to center the strip 100 percent. This asymmetric system causes electromagnetic forces on the strip. For the majority of systems these forces will center the strip. For a low frequency and / or a high relative permeability the direction of the force can change and dislocate the strip between the inductors.

The relative permeability in a rage from 1 till 30 has only a small influence on the Joule heat distribution in the strip, but for accurately investigations the correct permeability must be known.

## References

[1] Schülbe, H., Nikanorov, A., Nacke, B.: *Flexible transverse flux heaters of metal strip*. Proceeding of the International Symposium on Heating by Electromagnetic Sources, Padua, 2004, pp. 293-300.

[2] Ruhnke, A.: *Systematische Untersuchung der induktiven Querfeld-Banderwärmung*. Fortschritt-Berichte VDI, Vol. 19, 1999, No. 119, pp. 120-128.

[3] Kasjanow, L.: *Numerische Untersuchung der elektrodynamischen Kräfte bei der induktiven Querfelderwärmung*. Studienarbeit an der Leibniz Universität Hannover, 2001, pp 11-25.

[4] Galunin, S., Zlobina, M., Blinov, K., Nikanorov, A., Zedler, T., Nacke, B.: *Numerical analysis of coupled physics for induction heating of moveable workpieces*. Proceeding of the International Scientific Colloquium: Modelling for Electromagnetic Processing, Hannover, 2008, pp. 59-64.

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