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Induction heating of thin slabs and sheets in the rolling line

Abstract

The demand for high-quality sheet has been increasing for some years. For this reason, additional heating facilities have been integrated into the rolling lines. Induction heating is in this connection an effective means for efficient and high-performance in-line reheating. The paper presents the physical fundamentals of transverse- and longitudinal-field induction heating. Reheating and edge heating for thin slabs and the reheating of sheet after a double-roll casting plant are examples demonstrating the efficiency of induction heating in the rolling line.

Introduction

Modern rolling lines are producing ever higher sheet qualities at ever higher throughput rates. They must react flexibly to the most varied material properties, and the mass ratio of sheet output to input must be as high as possible. With the aid of induction heating, a high thermal energy can be introduced into the product within a small space. It is also possible to target the heating to specific sections of the material, for example to the strip edges. What are the physical fundamentals governing the induction heating process? Which necessary technical measures can be derived therefrom for inductor design? Where and for which applications is induction heating already in use? These questions are to be answered in the following.

Physical fundamentals

All electrically conducting materials can be heated with the aid of induction. To calculate the heat source distribution in metals, the modified Maxwell field equations for moving conductors are used.

Field equations:

$$\mathrm{rot}\, H = J \tag{1a}$$

$$\mathrm{rot}\, E = -\frac{\partial B}{\partial t} \tag{1b}$$

Continuity equations:

$$\mathrm{div}\, J = 0 \quad \text{and} \quad \mathrm{div}\, B = 0 \tag{2}$$

Material equations: $J = \sigma \cdot E$ and $B = \mu \cdot H$ (3)

It can be shown that the heat arising at a given point in space in the metallic conductor is equal to the energy conversion at this point. The energy can be calculated using equation (4).

$$P = \rho \cdot \left| J^2 \right| \quad \text{with} \quad \rho = \frac{1}{\sigma} \tag{4}$$

For a better physical understanding of the interdependencies of the electrical current density *J* and the magnetic field strength *H*, the equation (1a) is divided into its components. From equations (6), (7) and (8), it can be seen that the components of the current density are linked only with the corresponding perpendicular magnetic field components. The following is thus revealed: Even if there is only one component to the magnetic field, the current density will possess two components. However, a current is then only able to flow, if the field components change in a correspondingly perpendicular direction.

$$J_x = \mathrm{rot}_x H = \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \tag{6}$$

$$J_y = \mathrm{rot}_y H = \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \tag{7}$$

$$J_z = \mathrm{rot}_z H = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \tag{8}$$

The physical interpretation of the differential equations facilitates the interpretation of numerical field calculations and the assessment of inductor designs for the heating of sheet materials.

Induction heating of plate material in a longitudinal field

In the case of longitudinal-field induction heating, the sheet or other product to be heated is enclosed by a coil. If an alternating current flows through the coil windings, a magnetic field is produced. The alternating magnetic field, which is aligned within the coil parallel to the centre axis of the strip (*"longitudinally" to the strip direction*), induces a current in the material. The ohmic resistance losses cause the material to heat up. Due to the so-called skin effect, the induced current flows perpendicularly to the field

direction, close to the surface of the workpiece (Fig. 1).

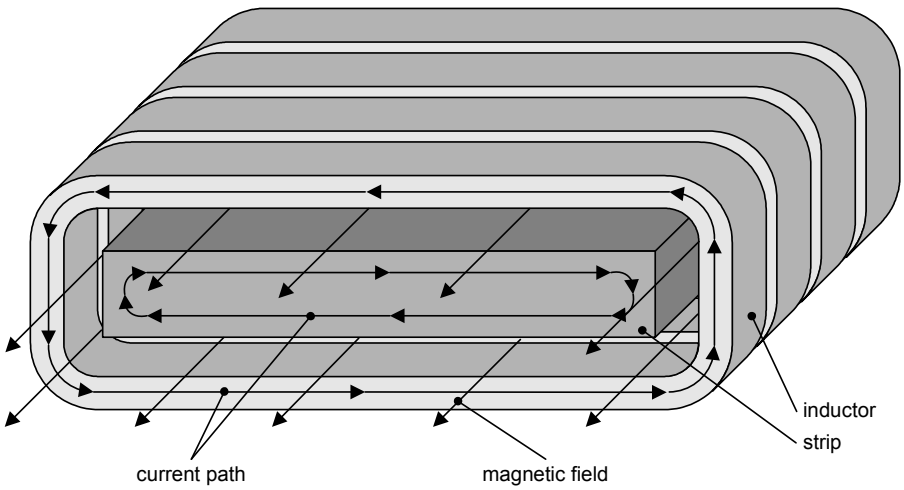

Fig. 1: Inductor-workpiece arrangement for longitudinal-field heating

The current flows in opposite directions on the upper and lower sides of the sheet. The fictitious layer thickness within which the current flows is designated as the penetration depth δ. If the sheet thickness is reduced to less than $4 \cdot \delta$, the current at the upper and lower sides begin to extinguish each other. At thicknesses below 2.5 times the penetration depth, the current is attenuated to such a degree, that economically viable heating is no longer possible. The penetration depth δ is calculated using equation (9).

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}} \tag{9}$$

Equation (9) shows that the penetration depth is dependent on the specific resistance of the material ρ, the permeability μ and the frequency f of the current. It is thus possible to specify a minimum necessary frequency for the heating of sheet materials.

$$f_{\min} \geq \left(\frac{2.5}{s}\right)^2 \cdot \frac{\rho}{\pi \cdot \mu} \tag{10}$$

The heating of steel sheet, where this sheet is to be reheated within or before the rolling train, should be performed at a frequency higher than that indicated for the thickness concerned on the depicted limit curve (Fig. 2).

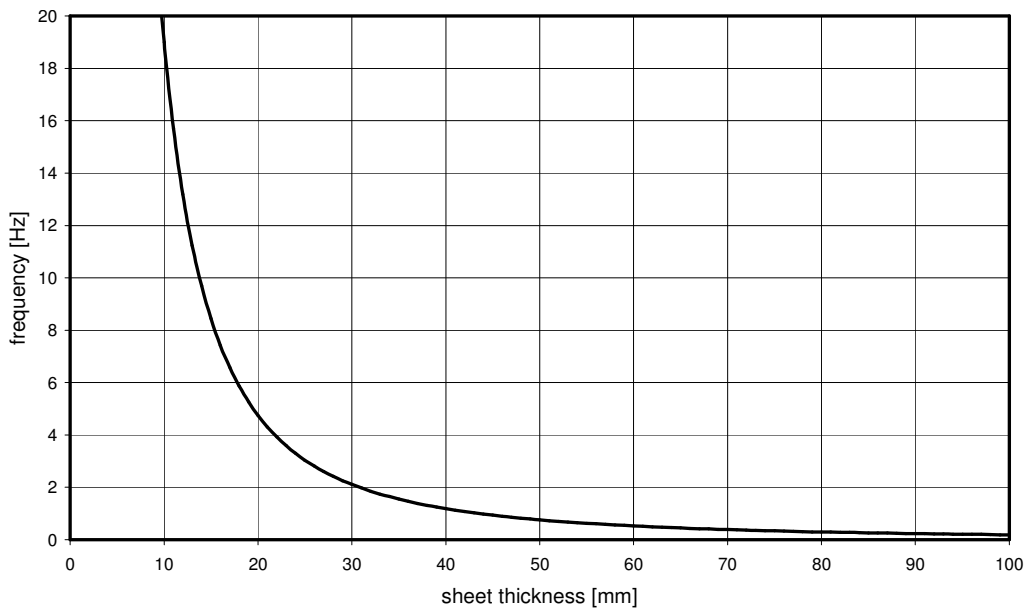

Fig. 2: Limit curve of minimum frequencies for the longitudinal-field induction heating of non-magnetised sheet

Induction heating of sheet material in a transverse field

Below the limit curve depicted in Fig. 2, the electrical efficiency of induction heating is diminished dramatically. Another possibility by which to induce current in the material is to use a magnetic field which is aligned not parallel to the strip direction, but instead at right-angles to this direction (see equations (6) and (7)). This is achieved by using not an enclosing coil, as in the case of a longitudinal-field heating, but instead flat coils arranged parallel to the upper and lower sides of the strip (Fig. 3).

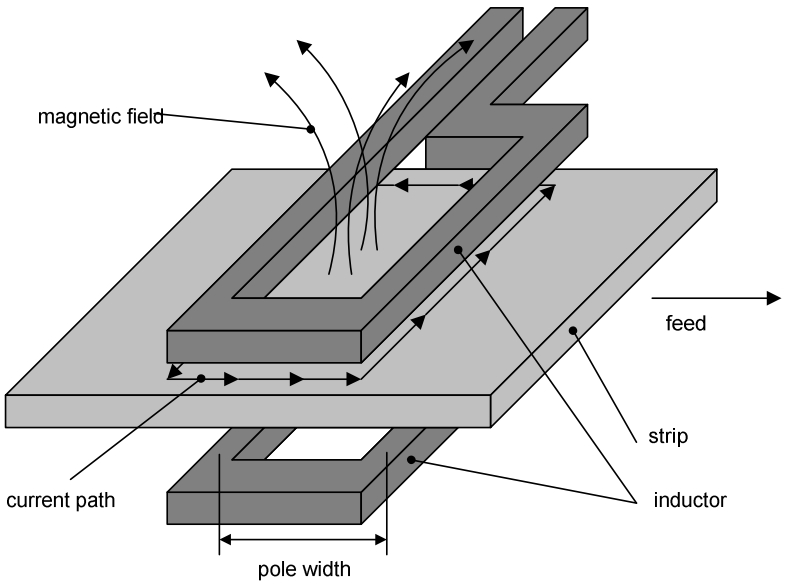

Fig. 3: Transverse-field heating with a double-sided unshrouded inductor arrangement

The currents induced in the material are in coarse approximation a projection of the inductor current onto the strip surface. To achieve an homogeneous temperature distribution over the width of the strip, specially matched inductor designs are used. These inductors are calculated and designed with the aid of numerical models. Through appropriate modification of the inductor design, it is also possible to set a desired temperature distribution over the strip width.

The induced current flows in the strip plane. The outward and return currents in the material must here be controlled by the field such that they do not extinguish each other. In this way, it is possible to realise economical induction heating for sheet materials significantly thinner than the penetration depth δ.

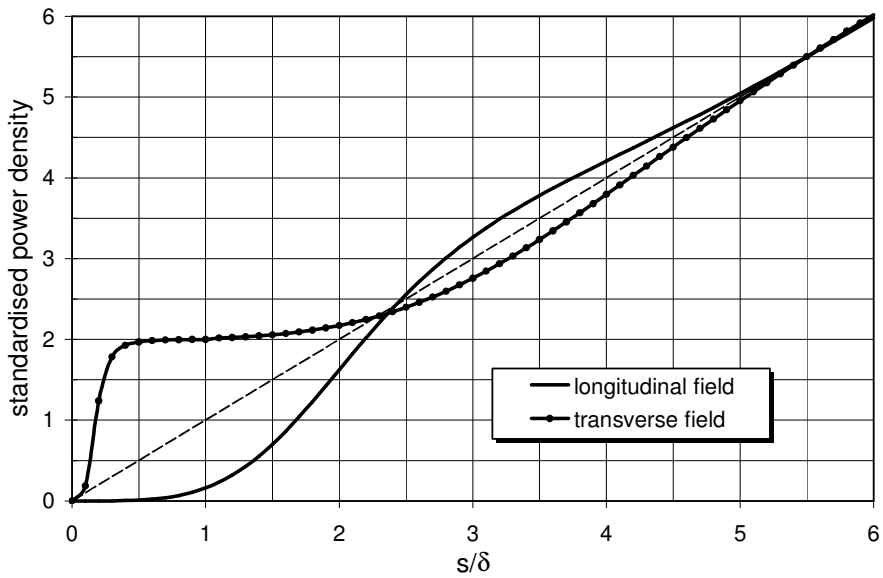

Fig. 4: Comparison of the power density at the strip surface for longitudinal and transverse fields

The curves shown in Fig. 4 indicate that, for longitudinal and transverse fields of equal strength, the attainable power densities when using transverse-field induction heating are greater than those achieved with a longitudinal-field arrangement up to an s/δ ratio of 2.4.

Examples of applications for longitudinal- and transverse-field induction heating

The following considers three examples from among the large number of implementations of induction heating plants in rolling lines which can be applied in like

or modified form to other task specifications.

Longitudinal-field heating in the rolling line between blooming stand and finishing train

With some materials, the rolling temperature at the finishing train is so low, that the sheet cannot be rolled down to the required thickness. One possible remedy in such cases is induction reheating of the plate material before it enters the finishing train. The material thickness at this point usually lies between 30 and 50 millimetres. The speed of the material transport lies between 0.8 and 1 m/s. Assuming a plate width of 1650 mm and a temperature range around 900 °C, the electrical energy required to achieve a temperature increase of 10 K can be calculated as follows:

$$P_{req.} = m \cdot \frac{c_p \cdot \Delta\vartheta}{\Delta t} \tag{11}$$

$$3105.5\left[\frac{kW}{10\,K}\right] = 0.3 \cdot 16.5 \cdot 10 \cdot 2.22 \cdot 3600 \cdot 7.85\left[\frac{dm \cdot kWh \cdot kg \cdot s}{s \cdot 1000\,kg \cdot 10\,K \cdot dm \cdot h}\right] \tag{12}$$

To raise the temperature of the material by 10 K, a power input into the plate of approx. 3100 kW is required. Modern induction plants operate with an electrical efficiency of approx. 70 %. Thus, an electrical input of approx. 4440 kW is necessary to heat a 1650 mm wide, 30 mm thick and 1.0 m/s fast strip by 10 K from 890 °C to 900 °C. Relating this power requirement to a 10 K temperature increase for a production tonne, the power consumption for plate reheating between the blooming stand and finishing train can be determined to be 3.2 kWh/(t 10 K).

Strip edge heating between blooming stand and finishing train

As reheating of the whole plate demands a very high power input, the heating is often limited to the plate edges. After all, the edges cool faster than the centre areas of the material. If we consider a width of 100 mm along the sides of the plate as the strip edge, then reheating of this edge will require an energy input of only approx. 267 kW/10 K per side. If both edges are to be heated by 50 K, for example, the required power consumption from the mains supply will amount to 2667 kW (1333 kW per side)
This energy can be transferred to the strip edges with a variety of different inductor

designs. There are two inductor designs, however, which are especially suitable for this heating task.

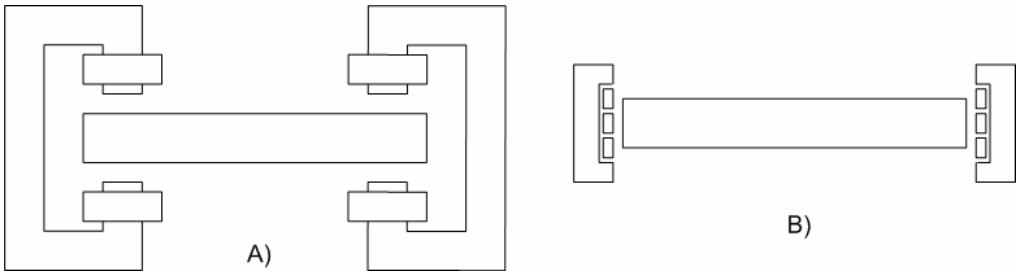

Fig. 5: Inductor designs for strip edge heating
A) Traverse-field heating with yoke inductors B) Longitudinal-field heating with linear inductors

Whereas the inductors of type A embrace the passing plate, those of type B stand along the side facing the strip edge. With type A, the magnetic field emanates perpendicularly from the magnet yoke, penetrates the material and is returned perpendicularly to the magnet yoke below the edge. It is aligned transversely to the plate. With type B, the magnetic field lines run parallel to the narrow strip edge, providing for longitudinal-field induction. Both inductor types are operated at frequencies of just a few 100 Hz. The electrical efficiency of both types lies at approx. 70 %.

Transverse-field heating of thin sheet

Fig. 6: Transverse-field heating of thin strip with 4 heating stations before the roll stand

When producing stainless steel sheet after roll casting, the strip must be reheated before rolling. The strip thickness is approx. 2.5 mm and the strip width is 1650 mm. The casting output rate is 50 m/min and the strip is to be heated from 1000 °C to 1200 °C. Applying equation (11), this produces:

$$3779\left[\frac{kW}{200\,K}\right] = 0.025 \cdot 16.5 \cdot 500 \cdot 38.9 \cdot 60 \cdot 7.85\left[\frac{dm \cdot kWh \cdot kg \cdot min}{min \cdot 1000\,kg \cdot 200\,K \cdot dm \cdot h}\right] \tag{13}$$

The efficiency of the power input from the mains supply is approx. 65 %. The necessary power consumption thus amounts to approx. 5800 kW. For each tonne and 200 K temperature increase, the specific power consumption is thus approx. 59.8 kWh/(t 200 K). Fig. 6 shows an implemented plant for transverse-field induction heating.

Summary

High power inputs are necessary for the reheating of plate and sheet materials in roll trains. Through the use of transverse- and longitudinal-field induction heating, the required energy can be introduced into the strip within a small space. It must be ensured, however, that the fundamental physical conditions are observed.

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