

Article

Analysis of the Influence of Process Parameters on Transverse Flux Induction Heating of Endless-Rolling Strip

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Abstract: This study focuses on the effect of an induction heating device on the entry of a thin strip continuous casting and rolling line. A finite element model for the electromagnetic–thermal coupling of transverse magnetic flux induction heating was developed by adopting COMSOL software 6.1 to systematically investigate the effects of process parameters on the magnetic field, eddy current field, and the transverse temperature distribution of the strip. The results show that when the gap is between 20 mm and 40 mm, the maximum value of magnetic induction in the overheating region at the edges of the strip increases from 0.28 T to 0.35 T and 0.38. When the strip width is 1000 mm, there is an approximately 29% increase in magnetic induction in comparison to a strip with a width of 800 mm, and both eddy current density and temperature exhibit abnormal fluctuations. The maximum temperature difference in the temperature uniformity region at the center of the strip is only 3 °C at different frequencies, and the temperature-rise curves almost completely overlap. With increasing current, the temperature difference between the weak temperature region and the temperature uniformity region at the center widens, indicating a deterioration in temperature uniformity. Meanwhile, the field conditions are simulated using a simplified model of continuous heating. The results indicate that the maximum temperature deviation in the overheating region at the edges of the strip is 6 °C, while the deviation in the temperature uniformity region is 2 °C. Furthermore, the simulation data reveal an average temperature rise of 1156 °C across the width of the strip, with a deviation of 1.4 °C compared to the measured results, which verifies the validity of the proposed model. The analysis results provide a reference basis for designing transverse magnetic flux induction heating devices and optimizing process parameters.



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Keywords: endless rolling; transverse flux induction heating; temperature uniformity; multi-physics coupling; finite element simulation

1. Introduction

Thin strip continuous casting and rolling technology integrates the processes of continuous casting and rolling to achieve a seamless production process from molten steel to finished strip steel. As a typical representative of short-process steelmaking technology [1–3], more than 10 production lines have been constructed in China to date. In order to ensure temperature uniformity of the rolled products and meet rolling process requirements, headless rolling production lines are usually equipped with dedicated modules for uniform reheating of the strip. For example, both the ESP and MCCR production lines are equipped

with induction reheating devices at the entry of the finishing mill [4,5]. According to the feedback from temperature detection at the finishing mill exit, these systems can achieve precise control of the strip temperature at the entry. Induction heating could be divided into two forms: longitudinal flux induction heating (LFIH) and transverse magnetic flux (TFIH). The longitudinal flux is primarily used for induction heating of long products such as bars and pipes [6–8], and the transverse magnetic flux is mainly used for heating strips and plates [9,10]. Compared with LFIH, the theoretical model and engineering design experience of the TFIH are relatively lacking. It is urgent that we clarify the influence of relevant process parameters on the heating patterns and temperature uniformity of the strip [11,12].

Recently, scholars at home and abroad have extensively studied induction heating by utilizing finite element analysis [13–17]. Mohring et al. [18] developed a three-dimensional numerical simulation model focusing on the impact of different current frequencies on the horizontal temperature uniformity of the strip, noting that TFIH advantages become more pronounced with increasing strip width–thickness ratio. P. Alott et al. [19] proposed a multi-coil TFIH coil design that is capable of uniformly heating strips of varying widths under a single configuration. Chen et al. [20] conducted orthogonal experiments and simulation analyses on gap and strip movement speed during the TFIH process; but the material thermal properties are not considered, limiting the accuracy of their computational results. Therefore, further improvements in accuracy are needed in these simulations. Wang et al. [21] conducted a simulation analysis of 45 steel and 15 MnV steel strips, with and without considering the variation of material property parameters with temperature. Peng et al. [22] established functional relationships between material properties and temperature during the model’s coupled iterative solution process by selecting corresponding material properties based on temperature.

Recent research has focused on optimizing process parameters and design improvements to enhance temperature uniformity across the width of TFIH-heated strips. Wang et al. [23] and Wu et al. [12] applied the VCPSO and GSA algorithms, respectively, to analyze the impact of process parameters on lateral temperature uniformity. Pevzner et al. [24] and Peng et al. [25] developed magnetic shielding to mitigate edge overheating, and established evaluation criteria for temperature uniformity.

The research suggests that the design of TFIH devices is still in the trial-and-error and research phase; with further refinement needed for process parameters, temperature control model, and strategies for maintaining temperature uniformity. Therefore, this paper focuses on the TFIH device in a domestic endless continuous casting and rolling production line. A finite element model for TFIH is established using COMSOL software 6.1 to analyze the impact of parameters such as gap, strip thickness, strip width, strip speed, frequency, and current on induction heating performance. This study serves as a foundation for designing and optimizing process parameters for TFIH devices.

2. Transverse Flux Induction Heating Model

Induction heating—which is recognized as an environmentally friendly, efficient, and rapid heating method—is increasingly being employed in hot rolling production lines [26–28]. The process layout of a specific continuous casting and rolling line is illustrated in Figure 1. The continuous casting billet is extracted from beneath the continuous casting machine, cut to length, and discharged at a predetermined temperature. After undergoing high-pressure water dephosphorization, the billet goes through the roughing mill. Following this, a rotary shear removes irregular portions from the leading and trailing ends. The billet then passes through the induction heating device before being dephosphorized again with high-

pressure water prior to entering the finishing mill. The finished product is subsequently cooled and cut using a high-speed flying shear before entering the coiling area.

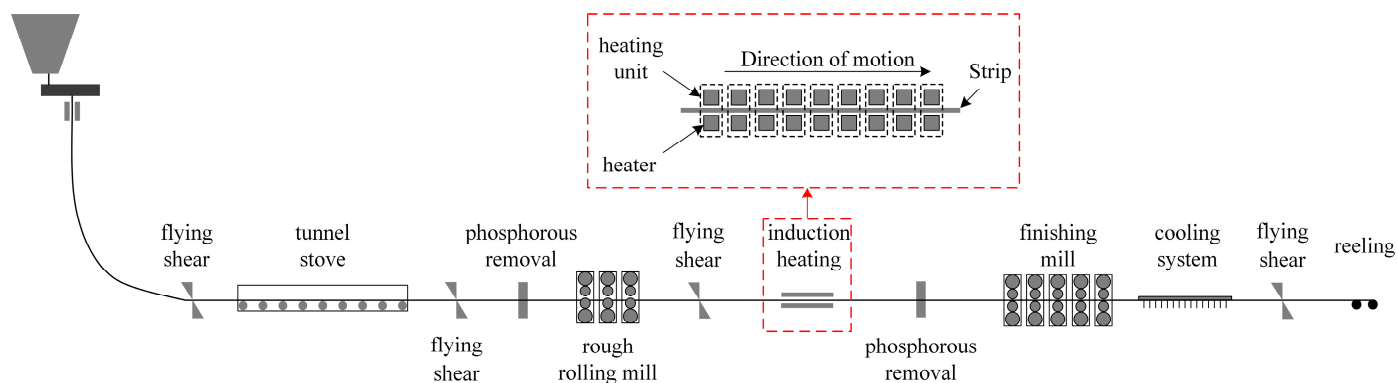


Figure 1. Process layout diagram of an endless rolling production line.

2.1. Physical Model

The TFIH system mainly involves physical fields; that is, the electromagnetic field and the temperature field. The AC/DC module in COMSOL 6.1/Multi-physics software implements Maxwell's equations to determine the distribution of the magnetic field in the electromagnetic circuit. The governing equations [29] of the electromagnetic field are

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \epsilon \mathbf{E}}{\partial t} \quad (1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (3)$$

$$\nabla \cdot \mathbf{E} = \xi \quad (4)$$

where $\mathbf{H}$, $\mathbf{E}$, $\mathbf{J}$, $\mathbf{B}$, ϵ and σ are the magnetic field intensity (A/m), intensity of the electric field (V/m), current density (A/m²), intensity of magnetic induction (T), dielectric constant (F/m), and volume charge density (C/m³), respectively.

To simplify computation, the magnetic vector potential $\mathbf{A}$ (V·s/m) and electrical scalar potential ϕ were introduced as auxiliary functions for setting up the differential equation as follows: By using the Coulomb gauge $\nabla \cdot \mathbf{A} = 0$, the above equations were combined and transformed to

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (5)$$

$$\mathbf{B} = \mu \mathbf{H} \quad (6)$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \phi \quad (7)$$

The current density in the workpiece was

$$\mathbf{J} = \sigma_e \mathbf{E} \quad (8)$$

$$\nabla \cdot \mathbf{J} = \nabla \cdot \left(-\sigma_e \frac{\partial \mathbf{A}}{\partial t} - \sigma_e \nabla \phi \right) = 0 \quad (9)$$

$$\nabla \times \left(\frac{\nabla \times \mathbf{A}}{\mu} \right) - \nabla \times \left(\frac{\nabla \times \mathbf{A}}{\mu} \right) \mathbf{J} \nabla \cdot + \sigma_e \frac{\partial \mathbf{A}}{\partial t} + \sigma_e \nabla \phi = 0 \quad (10)$$

where σ_e is the electrical conductivity (S/m) and μ is the magnetic permeability (H/m).

The boundaries of the electromagnetic field are set in air. For a finite element model of air, a Neumann boundary condition was set at $Y = 0$ where the magnetic induction lines at the boundary are perpendicular to the boundary. The boundary condition for the normal component of the given magnetic flux intensity is as follows:

$$\mathbf{B} \cdot \mathbf{n} = 0 \quad (11)$$

The boundary condition for the tangential component of the given magnetic flux intensity is as follows:

$$\mathbf{H} \cdot \mathbf{n} = 0 \quad (12)$$

The analysis of the temperature field is based on the law of conservation of energy, which mainly includes the following three parts: the convective heat transfer between the rolled part and the air, the radiative heat transfer between the rolled part and the air, and the conductive heat transfer along the temperature gradient in the rolled part. The temperature field is calculated as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q \quad (13)$$

where ρ , C_p , T , v , k , and Q are the density of the material (kg/m^3), specific heat capacity ($\text{J}/(\text{kg} \cdot ^\circ\text{C})$), temperature ($^\circ\text{C}$), speed of the moving strip (m/s), coefficient of heat conduction ($\text{W}/(\text{m} \cdot ^\circ\text{C})$), and the heat source (J/m^3), respectively.

Equation (8), with suitable boundary and initial conditions, represents the three-dimensional temperature distribution at any time and at any point in the work-piece.

2.2. Geometric Model and Mesh Generation

According to the layout characteristics of the induction heating device in the aforementioned continuous casting and rolling line, this paper takes a set of induction heating units as the research object to establish a geometric model, as shown in Figure 2. The two heating coils are arranged in parallel above and below the strip and are embedded with the magnetic core. As shown in Figure 2a, research path 1 is established at the outlet of the induction heating device along the width of the strip, and research path 2 is set up in the projection area of the device. Additionally, sections 1 and 2 are defined to facilitate analysis of magnetic field strength distribution and eddy current distribution in subsequent sections.

The mesh generation for the induction heating device model is illustrated in Figure 2b. Due to the significant influence of mesh layout on computational accuracy, the mesh for the strip has been refined in the model. A free triangular mesh is used for the surface of the strip, with four layers of mesh defined within the skin depth in order to enhance computational precision. To optimize computational load and efficiency, the mesh density gradually decreases outward from the center of the strip. The total number of elements in the model is 1,580,028. In Figure 2 and Table 1, L is the length of the induction heating device, h is the length of the induction heating device, l is the slab width, and l_0 is the length of the magnetic core.

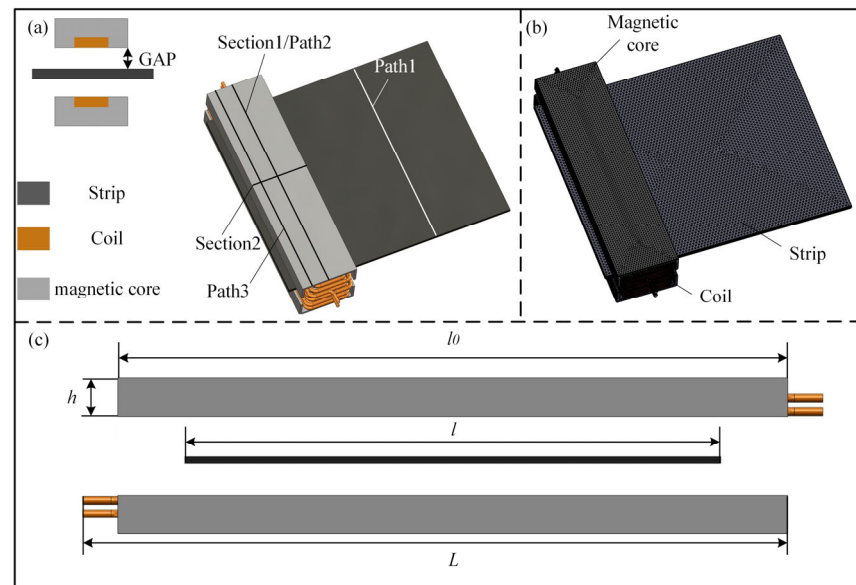


Figure 2. The geometric model and mesh division of the induction heating device: (a) geometric model; (b) mesh division; (c) geometric parameters of induction heating model.

Table 1. Geometric parameters of induction heating.

Parameter	Value	Unit
L	2000	mm
l	1600	mm
l_0	1800	mm
h	50	mm

2.3. Material Parameters

To improve the computational accuracy of the model, thermal and electromagnetic properties related to the strip temperature are taken into account during modeling. In COMSOL, the relationship between material properties and temperature is established in the form of interpolation functions, allowing for dynamic selection of corresponding material parameters based on temperature variations occurring during the solution process [30].

The strip is made of ASTM1045, as depicted in Figure 3a,b [31]. The chemical composition of AISI 1045 steel is given in Table 2 [32]. The magnetic core is composed of silicon steel, with material parameters illustrated in Figure 3c,d [33,34]. The chemical composition of silicon steel is given in Table 3. It is noteworthy that the magnetic core is constructed from insulated silicon steel sheets stacked together. In order to simplify the modeling approach and improve computational efficiency, the structural characteristics of the magnetic core are typically ignored, treating it as a solid structure without internal insulation. Setting the resistivity of the silicon steel sheets as their actual resistivity would result in increased eddy current losses within the magnetic core, which is inconsistent with the actual situation. The conductivity between the silicon steel sheets is significantly reduced. In this model, based on the existing literature [35–37], the electrical conductivity of the magnetic core is set to 1.5×10^5 S/m.

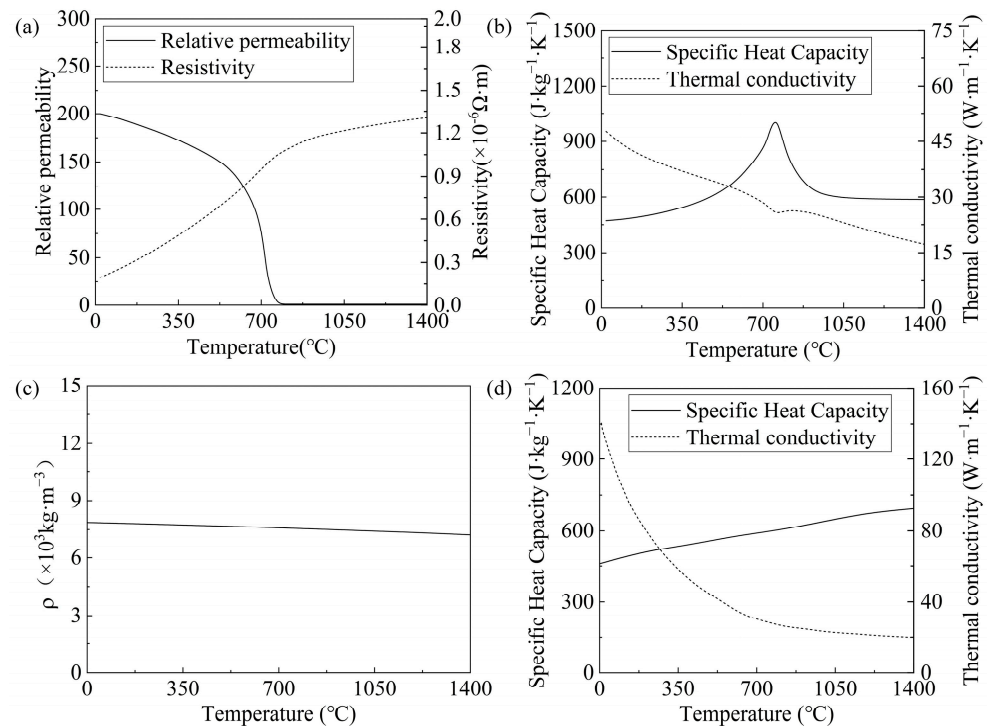


Figure 3. Material parameters of ASTM1045 and silicon steel: (a) relative permeability and resistivity of ASTM1045; (b) specific heat capacity and thermal conductivity of ASTM1045; (c) density of silicon steel; (d) specific heat capacity and thermal conductivity of silicon steel.

Table 2. Chemical composition of AISI 1045 steel.

Element	Carbon (C)	Manganese (Mn)	Sulphur (S)	Phosphorous (P)	Iron (Fe)
Content (%)	0.420–0.50	0.60–0.90	≤ 0.050	≤ 0.040	98.51–98.98

Table 3. Chemical composition of Fe-6.5% silicon.

Element	Cu	Manganese (Mn)	Silicon (Si)	Phosphorous (P)	Aluminum (Al)
Content (%)	0.52	0.035	6.5	0.077	0.011

2.4. Boundary Conditions and Solution Methodology

In the process of model construction, to ensure the calculation convergence, a rectangular air domain is established outside the induction heating device. The finite element solution is performed within this air domain—with its outer boundaries treated as an infinite far field, and magnetic insulation boundary conditions applied—while the initial magnetic field value is set to zero. As mentioned earlier, the temperature of the strip before induction heating in this production line can reach up to 900 °C, with a running speed exceeding 1 m/s. Due to the high ambient temperature of the strip steel during prolonged operation and the short duration of its exposure to the induction heating device, the effects of convective and radiative heat transfer are neglected in the model. This study focuses on examining how the process characteristics of the induction heating device influence the magnetic field, eddy current field, and the transverse temperature distribution of the strip. Therefore, the model does not account for the uneven initial temperature distribution across the strip's width. These simplifications enhance the model's focus on key parameters while significantly improving its computational efficiency.

The basic parameters for the induction heating used in this study are shown in Table 4.

Table 4. Basic parameters of induction heating.

Parameter	Value	Unit
Coil current	8500	A
Current frequency	400	Hz
Coil material	Copper	-
Coil diameter	25	mm
Speed of the strip	0.5	m/s
Thickness of the strip	20	mm
Initial temperature of the strip	900	°C
Gap	30	mm
Total heating time	4	s

The calculation process begins by inputting material and operational parameters. The coil geometry solver is then used to analyze the coil and compute the magnetic flux density distribution at a specific moment. Based on the magnetic flux density distribution under varying strip speeds, the magnetic field variations at different positions of the strip are determined, enabling the calculation of induced currents.

These induced currents are applied as loads for transient temperature field analysis. The results at this stage are compared against convergence criteria. If the criteria are met, the relevant material properties are updated. If not, iterative calculations of the temperature field continue until convergence is achieved.

This process repeats iteratively until the specified time steps are completed, at which point the results are output. The workflow for the multiphysics coupling calculation of transverse flux induction heating is illustrated in Figure 4.

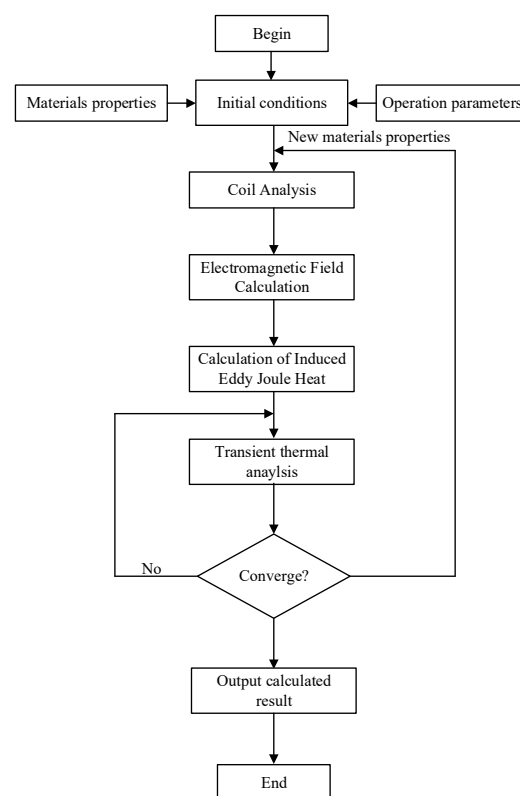


Figure 4. Procedures of electromagnetic and thermal analysis for induction heating process.

2.5. Finite Element Model Validation

Figure 5 illustrates the layout of the on-site induction heating device in an endless rolling production line. The Effective heating area represents the projection of the coil onto the strip, while Line 1 denotes the cross-section at the outlet of the on-site induction heating device. Full-section reheating of the strip is achieved by passing it through nine heating units at a constant speed.

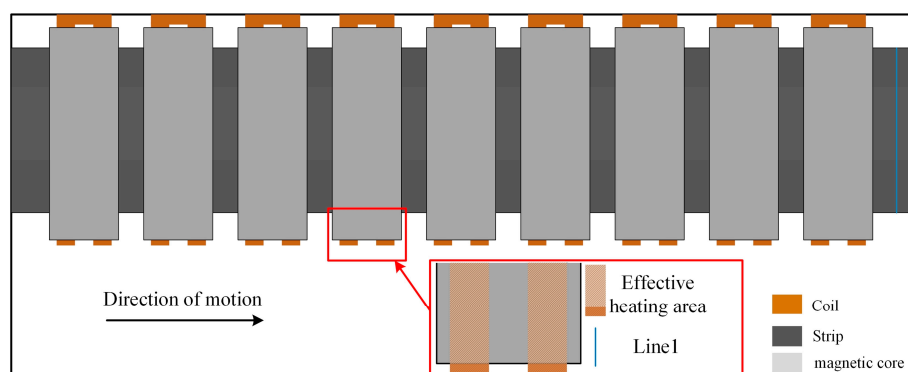


Figure 5. A schematic diagram of the induction heating part of an endless rolling production line.

In the on-site control system, full-section temperature scanners are only installed at the inlet and outlet areas, making it difficult to obtain individual temperature rise results for each heating unit. Therefore, it is assumed that all induction heating units produce the same temperature rise [38,39]. Accordingly, the temperature rise effect of a single induction heating unit is considered to be one-ninth of the total temperature rise achieved by the entire induction heating system.

Figure 6 illustrates a comparison between the simulation results and the measured data, showing that the maximum temperature deviation in the overheating region at the edges of the strip is 6 °C, while the deviation in the temperature uniformity region is 2 °C. Furthermore, the simulation data reveal an average temperature rise of 1156 °C across the width of the strip, with a deviation of 1.4 °C compared to the measured results, which verifies the validity of the proposed model.

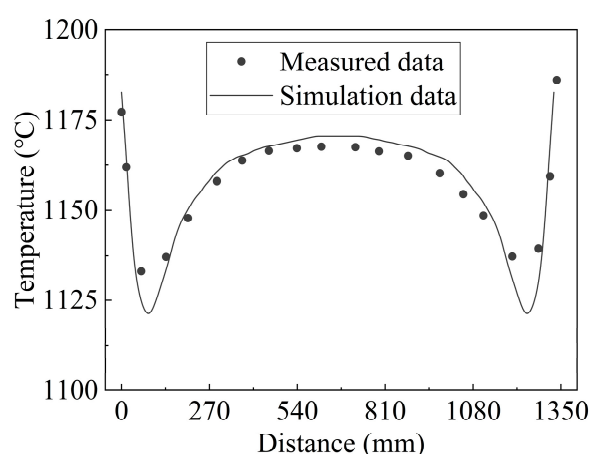


Figure 6. The simulation data are compared with measured data.

3. Results and Discussion

The contour plots of the geometric model, magnetic field, eddy current field, and temperature field—as well as the curve distribution across the width of the strip—are illustrated in Figure 7. In an infinitely large strip plane, the electromagnetic field distribution

follows the “coil projection principle”. However, due to the presence of strip boundaries, the electromagnetic field is distorted at the edge of the strip, resulting in uneven distribution. The skin effect further intensifies the electromagnetic field difference between the strip edges and the center [40], resulting in an overheating region at the edges (U1). A temperature uniformity region is established at the center of the strip (U2) where the eddy current density and magnetic induction are uniform. In the transitional segment between the two aforementioned temperature regions, the electromagnetic field values are notably lower, resulting in the formation of a temperature uniformity region at the center of the strip (U3). Line 2 and Line 3 run parallel to the width direction of the strip, located at the geometric center of the coils, while Line 4 represents a cross-section along the width direction of the strip at the outlet of the induction heating device. As shown in Figure 7f, it can be observed that the temperature distribution across the width direction of the strip displays a “W” shaped pattern, consistent with regional divisions depicted in contour plots. This allows for the categorization of temperature distribution along the strip’s width into three distinct regions: an overheating region at the edges (U1), a region of weak temperature (U2), and a region of uniform temperature located at the center (U3).

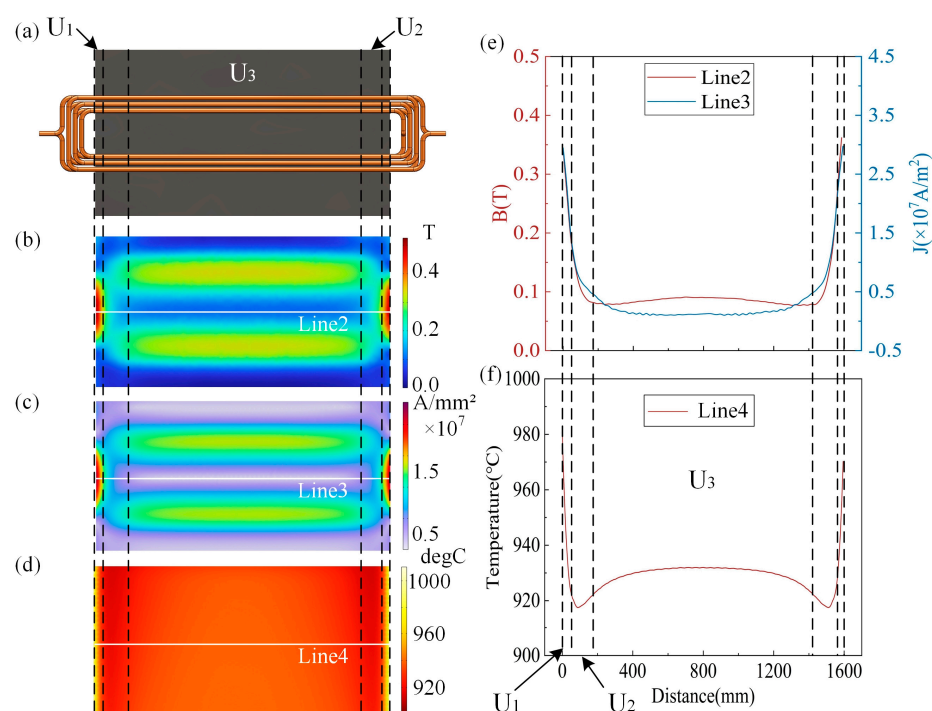


Figure 7. Eddy current, magnetic field, and thermal distribution nephogram and graph: (a) geometric model; (b) magnetic field; (c) eddy current field; (d) temperature field; (e) distribution curves of magnetic flux density and eddy current density; (f) temperature distribution curve.

Figure 8 depicts the distribution of magnetic flux lines at Sections 1 and 2 in Figure 8a. In Figure 8a, a significant transverse flux is evident across the width of the strip, with a noticeable concentration of magnetic flux lines at both ends due to the skin effect. Figure 8b demonstrates that, under the magnetizing influence of the magnetic core, a distinct transverse flux forms in the direction of the strip’s movement. Additionally, a small number of flux lines escape into the air and create loops around the coil at both sections.

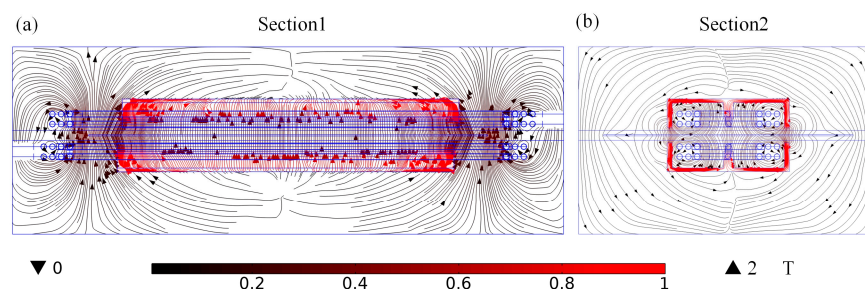


Figure 8. The distribution of magnetic lines on the cross-section after the induction heating state is stable: (a) section 1; (b) section 2.

3.1. The Impact of Gap on Heating Performance

As the gap decreases, more magnetic flux lines pass through the strip, resulting in a higher magnetic induction strength on the strip, which improves its heating capacity. The gap does not affect the distribution of the magnetic field and eddy current field. From Figure 9a, it is observed that when the gap ranges from 20 mm to 40 mm, the maximum magnetic induction strength in the overheating region at the edges of the strip increases from 0.28 T to 0.35 T and 0.38 T, while the increase in magnetic induction strength decreases from 25% to 8%. This is primarily attributed to the 45 steel gradually approaching a state of magnetic saturation, leading to a decrease in effective magnetic permeability. Consequently, further reduction of the gap does not significantly increase the magnetic flux. When the gap ranges from 50 mm to 60 mm, there is a decrease in maximum magnetic induction strength in the overheating regions at the edges—from 0.366 T to 0.358 T—with a reduction of 2%. The close alignment of the two curves is primarily attributed to the limited influence of the external magnetic field on the magnetic induction strength of the strip. The magnetic induction strength in the overheating region at the edges is predominantly determined by the distribution of magnetic flux within the strip. Consequently, increasing the gap further has a diminishing effect on the overheating region at the edges of the strip. The distribution patterns of eddy current density and magnetic induction strength are consistent. As depicted in Figure 9c, as the gap decreases, there is a gradual increase in temperature within the temperature uniformity region at the center of the strip, leading to an increase in temperature difference between this region and weak temperature areas, from 5 °C to 12 °C. This indicates that the lower the temperature uniformity across the width of the strip, the better the temperature rise capability.

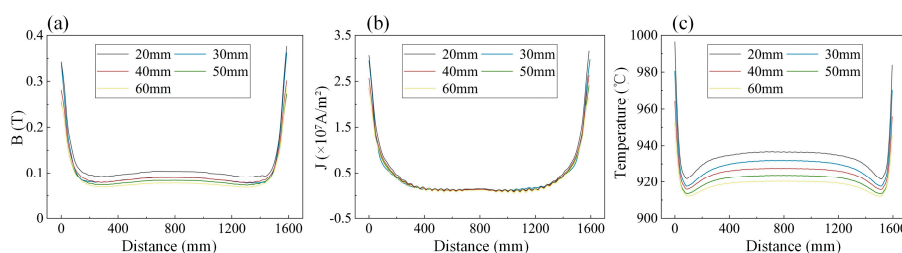


Figure 9. The simulation results in the width direction of the strip under different gaps: (a) magnetic induction strength distribution curve; (b) eddy current density curves; (c) temperature distribution.

3.2. The Impact of Strip Thickness Strip on Heating Performance

Simulations were carried out to analyze the impact of strip thickness on the induction heating effect within a range of 20 mm to 60 mm. As depicted in Figure 10a,b, a decrease in strip thickness facilitates easier penetration of magnetic lines through the strip. The numerical analysis reveals an increasing trend in magnetic field strength and eddy current density in the overheating region at the edges of the strip, as the thickness decreases.

Moreover, there is a gradual increase in magnetic induction strength in the temperature rise region at the center of the strip. Additionally, spatial constraints at the edges lead to a concentration of eddy currents, resulting in an expanded area of eddy current accumulation that converges toward the center. Figure 10c demonstrates that thinning the strip improves heating capacity within the temperature uniformity region at its center while worsening temperature uniformity, leading to a more pronounced “W”-shaped temperature rise distribution curve.

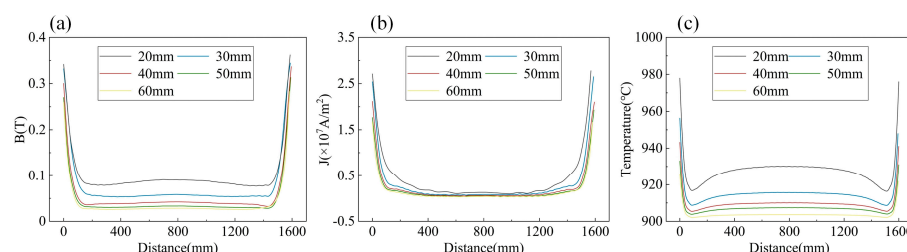


Figure 10. The simulation results in the width direction of the strip under different strip thicknesses: (a) magnetic induction strength distribution curve; (b) eddy current density curves; (c) temperature distribution.

3.3. The Impact of Strip Width on Heating Performance

To analyze the impact of different strip widths on the induction heating effect, simulations were conducted for various strip widths of 800 mm, 1000 mm, 1200 mm, 1400 mm, and 1600 mm. As depicted in Figure 11a,b, a decrease in strip width resulted in a downward trend in magnetic induction within the temperature uniformity region at the center of the strip, while irregular changes are observed in the overheating region at the edges. At a strip width of 1000 mm, the maximum magnetic induction in the overheating region at the edges is approximately 0.45 T, representing an increase of about 29% compared to an 800 mm wide strip. The abnormal fluctuations in the overheating region at the edges are primarily attributed to variations in staggered arrangement of upper and lower coils along with changes in strip width. The change in coil configuration results in variations in magnetic field coupling at the edges of the strip, leading to irregular changes in magnetic induction. A similar phenomenon is observed in the eddy current density in the overheating region at the edges. As shown in Figure 11c, the temperature distribution curve in the shape of a “W” gradually flattens at the two inflection points. Numerically, there is a nonlinear downward trend in temperature at the center of the strip’s uniform region. While temperature uniformity improves in this region, there is a decrease in average temperature rise, resulting in reduced heating capability. Additionally, similar irregular fluctuations are observed in the overheating region at the edges of the strip.

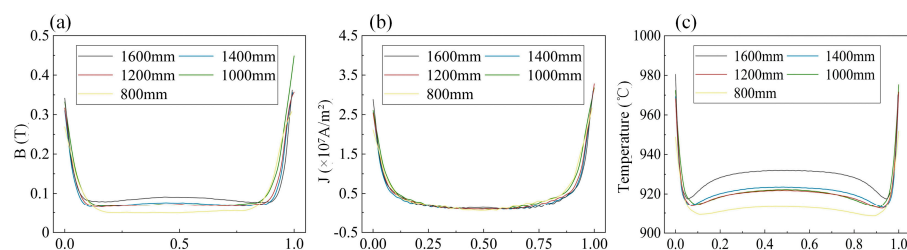


Figure 11. The simulation results in the width direction of the strip under different plate widths: (a) magnetic induction strength distribution curve; (b) eddy current density curves; (c) temperature distribution.

3.4. The Impact of Strip Speed on Heating Performance

When the strip runs at different speeds, the figures show the curves of eddy current density and magnetic induction strength in the width direction. As depicted in Figure 12a,b, the curves exhibit almost complete overlap, indicating that variations in the running speed of the strip do not affect the numerical values of magnetic induction strength and eddy current density.

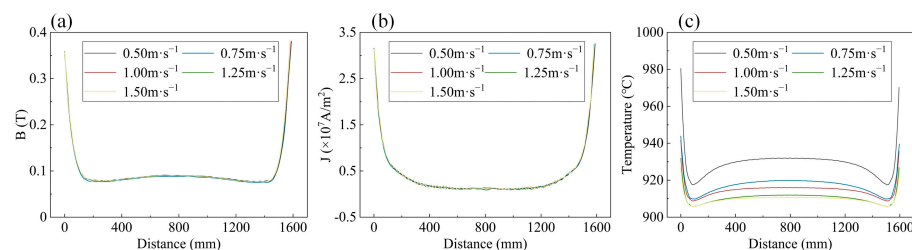


Figure 12. The simulation results in the width direction of the strip under different strip speeds: (a) magnetic induction strength distribution curve; (b) eddy current density curves; (c) temperature distribution.

The speed of the strip directly impacts its residence time in the effective heating area of the induction heating device. A slower speed results in prolonged exposure to the effective heating area, leading to improved heating performance. At a running speed of between $1.25 \text{ m}\cdot\text{s}^{-1}$ and $1.5 \text{ m}\cdot\text{s}^{-1}$, the temperature curves in the uniformity region at the center of strip nearly overlap, with a maximum temperature difference of approximately 2°C . Therefore, the higher the running speed, the less significant its impact on heating performance. Moreover, lower running speeds accentuate the “W” shape of the temperature curve and increase the temperature disparity between weak and uniform regions, indicating that the temperature uniformity in the width direction of the strip worsens, while the average temperature increases.

3.5. The Impact of Frequency on Heating Performance

As the frequency decreases, the skin depth of the strip increases, reducing the skin effect and enhancing the ability of the magnetic field lines to penetrate the strip [41]; the diffusion of magnetic field lines toward the center of the strip enhances the magnetic induction strength. Conversely, at higher frequencies, intensified skin effect leads to a greater accumulation of eddy current density at the edges of the strip, resulting in increased eddy current density. From Figure 13a, it can be observed that in the temperature uniformity region at the center of the strip, magnetic induction strength increases with frequency, with a more pronounced rate of increase. The magnetic induction strength curves in the overheating region at the edges of the strip exhibit significant overlap within the frequency range of 400 Hz to 1000 Hz, while a noticeable increase is observed at a frequency of 200 Hz. The distribution of eddy current density curves is presented in Figure 13b; showing an intensification of eddy current density concentration at the edges as the frequency increases, leading to higher eddy current density in the overheating region. Figure 13c displays temperature distribution curves across the width of the strip at different frequencies, revealing convergence of temperatures in the central heating region and a maximum temperature difference of only 3°C . With increasing frequency, there is a rise in temperature in the overheating region at the edges, indicating reduced temperature uniformity across the width.

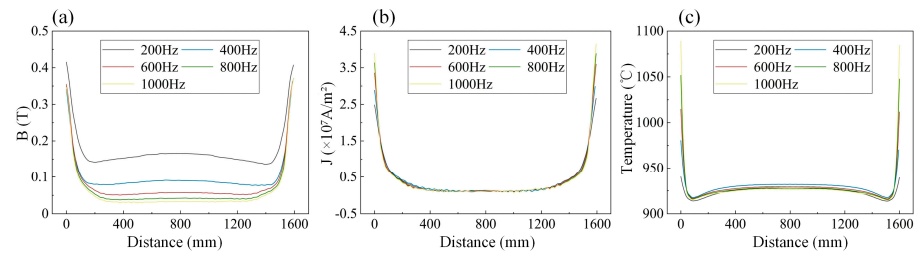


Figure 13. The simulation results in the width direction of the strip under different frequencies: (a) magnetic induction strength distribution curve; (b) eddy current density curves; (c) temperature distribution.

3.6. The Impact of Current on Heating Performance

The effect of current on the electromagnetic field is depicted in Figure 14a,b. It can be observed that both the magnetic induction and eddy current density increase with higher currents. Moreover, in the overheating region at the edges of the strip, there is a noticeable trend of eddy current density “converging” towards the center of the strip. As illustrated in Figure 14c, an increase in current leads to a significant rise in overall heating effect across the width direction of the strip. Furthermore, there is a widening temperature difference between weak temperature regions and uniformity regions at the center—progressively increasing from 2.5 °C to 5.5 °C, 8 °C, 15 °C, and 19 °C—resulting in a more pronounced “W”-shaped temperature distribution curve. This indicates a decrease in temperature uniformity across the width of the strip, while simultaneously increasing heating effects correspondingly.

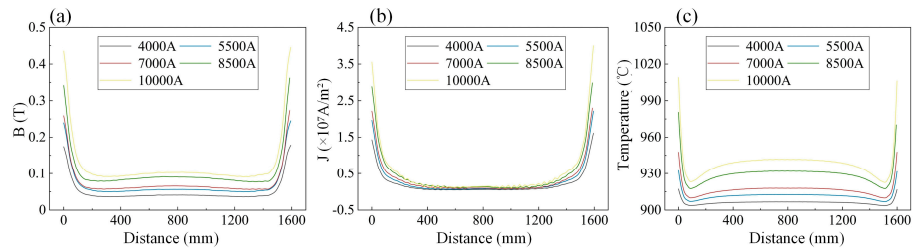


Figure 14. The simulation results in the width direction of the strip under different current: (a) magnetic induction strength distribution curve; (b) eddy current density curves; (c) temperature distribution.

3.7. The Impact of Different Parameters on the Heating Capability and Temperature Uniformity of the Strip

Sections 3.1–3.6 reveal that changes in gap, strip thickness, strip width, strip speed, frequency, and current have varying degrees of impact on the temperature rise across the strip width. In continuous casting and rolling endless production lines, the rapid temperature drop at the strip edges necessitates the adjustment of process parameters to meet different reheating demands for the strip edges.

To further analyze the effects of process parameters on the temperature rise capability and temperature uniformity in the weak temperature region and the temperature uniformity region at the center, the average temperature rise T_{AV} and standard deviation T_s of the weak temperature region (U_2) and the temperature uniformity region at the center (U_3) in Figure 7f are used as evaluation metrics. A smaller T_s indicates lower temperature fluctuations and higher temperature uniformity. The definitions of T_{AV} and T_s are as follows:

$$T_{AV} = \frac{1}{m} \cdot \sum_{n=1}^m T_n \quad (14)$$

$$T_s = \frac{1}{m} \cdot \sqrt{\sum_{n=1}^m (T_n - T_{AV})^2} \quad (15)$$

In the equations: T_{AV} represents the average temperature of all sampling points ($^{\circ}\text{C}$); m is the total number of sampling points; T_n is the temperature at sampling point n ($^{\circ}\text{C}$), where $1 \leq n \leq m$.

According to Figure 15, as the gap increases from 20 mm to 60 mm, the average temperature rise decreases from 933.5 $^{\circ}\text{C}$ to 918.4 $^{\circ}\text{C}$, and the standard deviation reduces from 4 to 2.4. This indicates that, with an increased gap, both the average temperature rise and standard deviation at the strip center decrease, leading to weaker heating capability but more uniform temperature distribution. When the strip thickness increases from 20 mm to 60 mm, the average temperature rise decreases significantly from 928.5 $^{\circ}\text{C}$ to 903.3 $^{\circ}\text{C}$, and the standard deviation reduces from 4 to 0.4. This shows that, as the strip thickness increases, the heating capability at the strip center declines substantially. With increasing strip width, both the average temperature rise and standard deviation at the strip center show an upward trend. When the strip width ranges from 1000 mm to 1400 mm, the average temperature rise varies by only 1 $^{\circ}\text{C}$, indicating consistent heating capability. Moreover, for widths between 1000 mm and 1200 mm, the standard deviation varies by just 0.04, demonstrating consistent temperature uniformity. As the strip speed increases from 0.5 $\text{m}\cdot\text{s}^{-1}$ to 1.5 $\text{m}\cdot\text{s}^{-1}$, the average temperature rise decreases from 928.5 $^{\circ}\text{C}$ to 909.4 $^{\circ}\text{C}$, and the standard deviation reduces from 4 to 1.4. This suggests that with higher strip speeds, both the average temperature rise and standard deviation decrease, resulting in weaker heating capability but more uniform temperature distribution. At different frequencies, the maximum difference in average temperature rise at the strip center is only 5 $^{\circ}\text{C}$, indicating a minimal impact on heating capability. However, the standard deviation decreases with increasing frequency, improving temperature uniformity at the strip center. When the current increases from 4000 A to 10,000 A, the average temperature rise at the strip center increases from 905 $^{\circ}\text{C}$ to 937 $^{\circ}\text{C}$, while the standard deviation rises from 0.87 to 5.48. This indicates that higher currents enhance the heating capability but reduce temperature uniformity at the strip center.

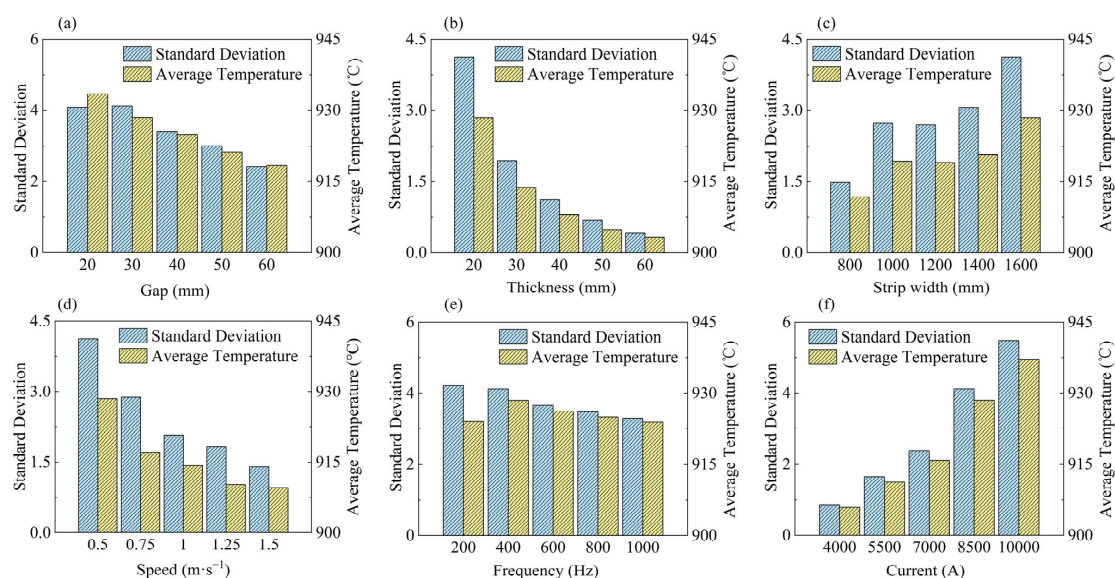


Figure 15. Results of the average temperature rise and standard deviation at the center of the strip: (a) results under different gaps; (b) results under different strip thicknesses; (c) results under different strip widths; (d) results under different strip speeds; (e) results under different frequencies; (f) results under different currents.

4. Conclusions

A finite element model for the electromagnetic-thermal coupling of the TFIH process is established by COMSOL software 6.1, with the exclusion of the impact of the stacked structure of the magnetic core on material parameters. The accuracy of the model is validated through field data. Further analysis revealed the influence of variations in process parameters—including current frequency, current magnitude, strip thickness, strip width, gap, and speed—on the distribution of the electromagnetic field, eddy current density, and temperature distribution across the width of the strip during the motion of the workpiece.

The study regions are categorized based on the temperature distribution across the width of the strip; specifically into the weak temperature region, temperature uniformity region, and overheating region at the edges. A smaller gap reduces temperature uniformity across the strip's width but enhances heating capacity. Thinning the strip improves heating in the central uniformity region but worsens temperature uniformity. As the strip becomes thinner, temperature uniformity declines, and the “W”-shaped temperature rise curve becomes more pronounced. At a strip width of 1000 mm, abnormal fluctuations in magnetic induction, eddy current density, and temperature appear in the overheating region at the edges. The running speed of the strip does not affect electromagnetic field distribution or magnitude, while frequency has no effect on central temperature uniformity region. Increasing the current significantly enhances overall temperature rise across the strip's width but reduces temperature uniformity.

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