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A Novel Coil Distribution for Transverse Flux Induction Heating

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Abstract

For solving the problem of inhomogeneous temperature distribution on the surface of the work piece at the transverse flux induction heating (TFIH) device outlet, a novel coil distribution of the inductor is presented in this paper. The relationship between coil geometry and temperature distribution was analyzed firstly. According to the theoretical analysis results, the novel coil geometry was designed in order to get a uniform temperature distribution. Then the non-linear coupled electromagnetic-thermal problem in TFIH was simulated. The distributions of the magnetic flux density and eddy current of the novel and the traditional rectangular coil geometry were presented. Finally, a prototype was developed according to the numerical results. The experimental results of the temperature distribution agreed with the numerical analysis.

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Keywords: novel coil distribution; TFIH; eddy current field; thermal field;

1. The Introduction of Transverse Flux Induction Heating Equipment

Transverse flux induction heating (TFIH) equipment contains symmetrically placed coils on both sides of the continuously moving thin strip. The alternating currents in two opposite coils are in phase and produce magnetic flux perpendicular to the surface of the work piece, which induces eddy current in the thin conducting strip. The caused joule heat warms the material up continuously.

Compared with longitudinal flux induction heating equipments, the TFIH equipments have considerable advantages, due to the need of lower frequencies and less reactive power. The geometry of the inductor doesn't encircle the work piece, so the TFIH equipment is particularly suitable for continuously processes. The main disadvantage of the TFIH is the resulting inhomogeneous temperature distribution on the surface of the strip cross-section at the inductor outlet, which is mainly influenced by the coil geometry and the position of the coil edges

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relative to the work piece width （Y. Wang et al., 2011 and Y. Wang et al., 2011 and L. Pang et al., 2010 and SL Ho et al., 2009).

Traditionally, the coil geometry used in TFIH equipment is rectangular, which is parallel to the strip (F. Dughiero et al., 1997). The coil to strip width ratio has a considerable influence in the temperature distribution at the strip edge. Long coils protruding beyond the strip edge lead to edge overheating, and short coils result in a temperature decrease. Even if the position of the coil edges relative to the work piece width is optimized, the temperature is still inhomogeneous. Our previous work demonstrated that such a single rectangular inductor can't result in a uniform temperature distribution (X. Yang et al.,2004 and Z. Wang et al., 2001). The traditional method to solve this problem is to use two inductors, each with different coil to strip width ratio (D. Schulze et al., 1996), or to use two coil groups switched alternately (W. Mai et al., 1998).

In this paper, the effect of the coil geometry on the distribution of eddy current and the finial temperature was studied and a new kind of coil geometry is designed for homogeneous temperature distribution. Test results show that the presented inductor can produce more uniform temperature distribution compared with traditional rectangular inductor structure.

2.The Analysis between Coil Geometry and Temperature Distribution

To simplify the analysis of the TFIH, the inductor and the work piece is simplified to a thin metal sheet with a closure coil (C_1) over it as shown in Fig.1. The projection of the coil on the sheet is C_2. The alternating current flows in the coil. It is assumed that the sheet is much larger than the coil so that the edge effect can be neglected. The distance between C_1 and C_2 is so short that the magnetic flux density at the coil plane is almost equal to that at the projection plane. The magnetic lines of force penetrating through the sheet have opposite direction outside and inside C_2, which are marked with cross and point signs respectively. Without loss of generality, the C_1 is considered to be circular and its radius is r_0, so the C_2 is circular too. Take a ring with the same center as C_2 in the sheet, inside radius r_2 and outside radius r_1. Let $d_r=r_1-r_2$, $a_r=(r_1+r_2)/2$ and $d_r << a_r$.

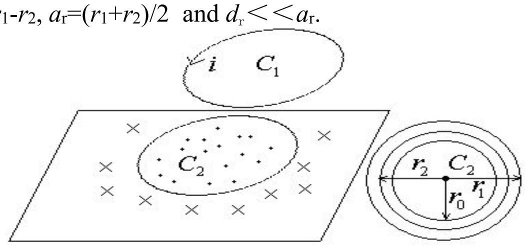


Fig.1 The relationship between eddy current distribution and the projection of the coil geometry

According to Faraday's law of induction, the electromotive force in the ring is

$$e = -\mathrm{d}\Phi/\mathrm{d}t \tag{1}$$

where Φ is the magnetic flux, t is the time. Under the condition of sinusoidal current supply, $\Phi=\Phi_M \sin\omega t$, where Φ_M is the magnitude of Φ , and ω is the angular frequency. The resistance of the considered ring is

$$R = \rho \frac{l}{S} = \rho \frac{2\pi a_r}{d_r h} \tag{2}$$

where ρ is the resistivity, h is the thickness of metal sheet, l is the perimeter, and S is the cross section area of the ring.

When the ring is outside C_2, the eddy current is expressed by

$$I = \frac{e}{R} = -\frac{\omega d_r h}{2\pi\rho} \cdot \frac{\Phi_M}{a_r} \cos(\omega t) \tag{3}$$

For a given frequency, constant metal sheet thickness and material resistivity, the expression $-\omega d_r h / 2\pi\rho$ is a constant value. Because the magnetic flux has different direction inside and outside the ring, the Φ_M will decrease as a_r growing. Thus, the eddy current will also decrease.

So it can be concluded: the more far from the centre the lower eddy current density outside coil geometry projection.

When the ring is inside C_2, there must be a magnetic flux density B_a, according to the continuity of the magnetic flux density $\vec{B}$ and integral mean value formula, which gives

$$\Phi = \int_s \vec{B} \cdot ds\, \vec{n} = B_a \pi r_2^2 \tag{4}$$

then

$$e = -\frac{d}{dt} B_{aM} \pi r_2^2 \sin(\omega t) \tag{5}$$

where B_{aM} is the magnitude of B_a. Since $a_r \approx r_2$, the eddy current in the ring is

$$I = \frac{e}{R} = -\frac{\omega d_r h}{2\rho} B_{aM} a_r \cos(\omega t) \tag{6}$$

where $-\frac{\omega d_r h}{2\rho}$ is also a constant value.

Take two circle C_3 and C_4 inside C_2, which have the same centre of C_2, radiuses r_3 and r_4, areas s_3 and s_4, respectively. Let $s_3 > s_4$, and $s_5 = s_3 - s_4$. The magnitude of B_a in s_3, s_4 and s_5 is B_{aM3}, B_{aM4} and B_{aM5}, respectively. The magnetic flux in s_3 equals the sum of those in s_4 and s_5, that is

$$B_{aM3} \pi r_3^2 = B_{aM4} \pi r_4^2 + B_{aM5} \pi \left(r_3^2 - r_4^2 \right) \tag{7}$$

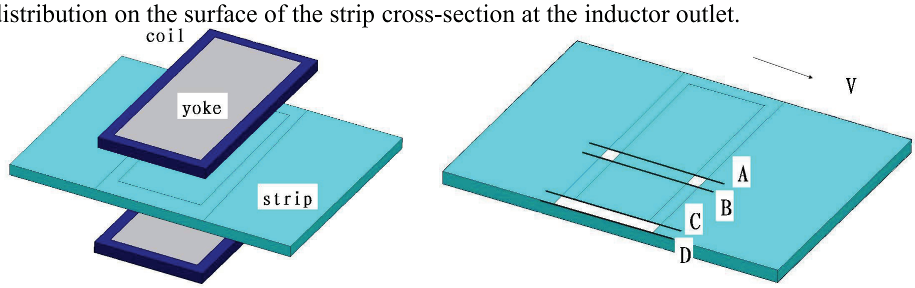
The magnetic flux density in C2 is an increasing function of its radius, $B_{aM4} < B_{aM5}$, so

$$(B_{aM5} - B_{aM4})\left(\frac{r_3^2 - r_4^2}{r_3}\right) > 0 \tag{8}$$

From Eq. (7) and Eq. (8), we can obtain $B_{aM3} r_3 > B_{aM4} r_4$. So it can be concluded: the eddy current increases as r_2 grows.

On the basis of above analysis, it is shown that the eddy current is mainly localized near the projection of coil. Our previous research also shown the eddy current density near coil projection is much larger than that in other regions. This result is helpful for coil geometry design to get uniform temperature distribution.

The traditional geometry of the coil in the TFIH equipment is rectangular, which is parallel to the strip as shown in Fig. 2(a). According to the relationship between eddy current distribution and coil geometry described above, the distribution of the joule heat is schematically shown in Fig. 2(b), where *V* represents the direction of the velocity of the strip. In this figure, A, B, C and D are the lines parallel to *V*, and the distance between A and B is equal to that between C and D. As is evident, the joule heat presented by the two white colour zones between A and B is much smaller than that presented by rectangular white colour zone between C and D which are very close to strip edge. The different amount of joule heat in the strip in the direction of the velocity would lead to inhomogeneous temperature distribution on the surface of the strip cross-section at the inductor outlet.



(a) Rectangular geometry coil in TFIH equipment (b) Joule heat source distribution on the strip surface

Fig.2 The relationship between coil geometry and joule heat distribution

From the analysis above, we can draw a conclusion that to obtain a uniform temperature distribution, the area of the projection of the coil geometry onto the strip surface in the direction of the velocity should approximately be equal. Presently the coil in TFIH equipment is such geometry or alike, so we can hold that the traditional rectangular coil can not produce a completely homogeneous temperature across the entire strip width at the inductor outlet.

3.The Novel Coil Distribution for TFIH

In this paper, a novel type of coil distribution is designed as shown in Fig. 3, where *V* represents the direction of the velocity. The solid model is symmetric by XOY plane, so only one half of the solid object is shown in the figure. The coil is basically with square shape, and the edges of coil are not parallel to those of the strip, intersecting with an angle of forty-five degree. Obviously, the projection area of this type of coil geometry onto the strip is equal along moving direction. For compensating the heat loss at strip edges, two corners of coil protrude beyond the strip edge.

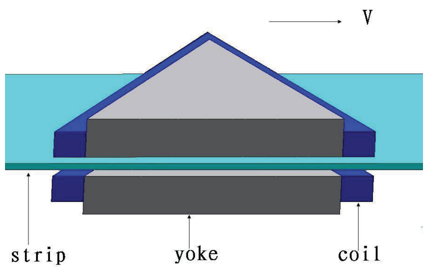
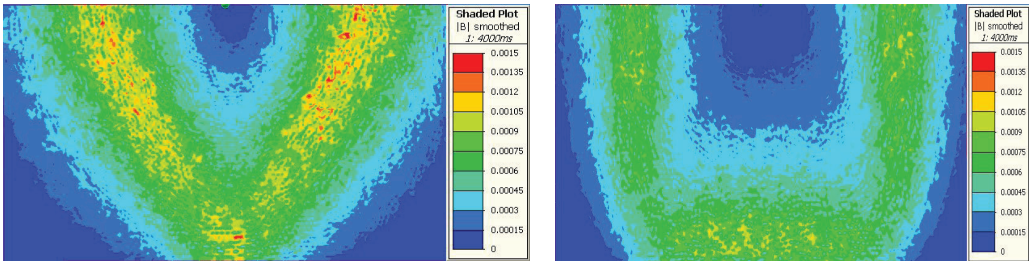


Fig.3 One half of the TFIH inductor Structure

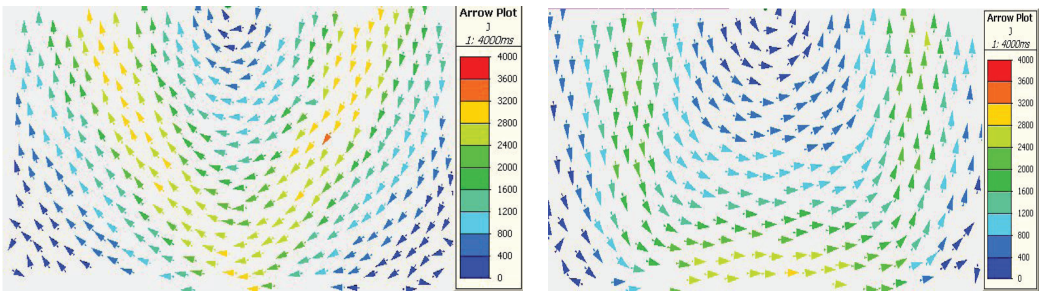
The simulation of this induction heating process is a coupled problem of electromagnetic field and thermal field. The coupled problem iteration process: using the calculation of eddy current distribution of electromagnetic field as heat source input, the thermal field is the calculated to get temperature distribution. Because the magnetic relative permeability, the electric conductivity, the thermal conductivity and the thermal specific heat of the work piece are influenced by temperature, they would change along with the rise of temperature. The material characteristics should be updated at the next eddy current iteration calculation to obtain more precise results.

When the parameters of conducting strip, alternating current and velocity are same, the simulated magnetic flux density and eddy current density distribution on the strip surface of novel coil distribution and traditional rectangular one are respectively shown in Fig.4 to Fig.5, which demonstrate that the eddy current distribution practically concentrates on the coil projection onto strip surface.



(a) The novel coil distribution (b) The traditional coil distribution

Fig.4 The simulated magnetic flux density distribution on the strip surface of two types of coil distribution



(a) The novel coil distribution (b) The traditional coil distribution

Fig.5 The simulated eddy current density magnetic flux density distribution on the strip surface of two types of coil distribution

The TFIH equipment is developed according to the numerical results as shown in Fig.6. When the steel strip width is 0.2m, its thickness is 0.5mm, its velocity is 5.32m/min, the exciting current is 100A, and the working frequency is about 0.7 KHz, the temperature distribution on the strip surface at the inductor outlet is shown in Fig.7. This picture is obtained by a thermal imaging camera which shows the temperature at the inductor outlet of the prototype is nearly uniform. The Fig. 8 is the compare of the simulated temperature and the measured value, which shows that the test results nearly agree with the numerical simulation results.

Fig.6 Transverse flux induction heating equipment

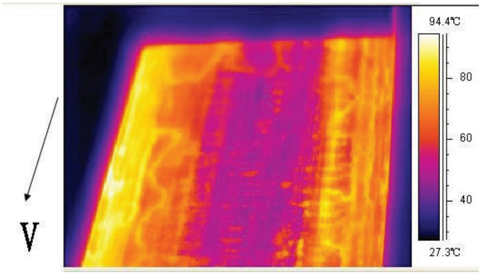


Fig.7 Temperature test results

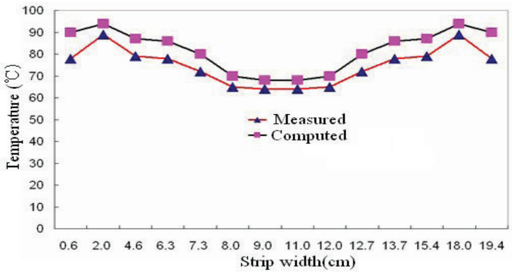


Fig.8 Comparison of computed temperature with the measured

4.Conclusions

(1) That the eddy current distribution mainly concentrates on coil projection onto strip surface in TFIH equipment is demonstrated. By the coil geometry and inductor structure we can estimate the eddy current distribution, which gives a hint to temperature profile for static strip.

(2) To obtain a uniform temperature distribution, the area of the projection of the coil geometry onto the strip surface in the direction of the velocity should approximately be equal. Judging from projection area of coil geometry is a practical method for inductor design.

(3) The simulation results of the non-linear coupled electromagnetic-thermal problem are verified by the experimental results with which new coil geometry was designed.

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