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***Abstract*- Litz wire is commonly employed as the heating coil of induction cookers. In order to realize further low cost and profile, the solid wire with simple construction and high space factor is required. However, the solid wire is may suffer from the large copper loss increased by the skin and proximity effect. Then, the previous study proposed the novel coil structure, which can suppress these effects, only by the FEM simulation. Therefore, the purpose of this paper is to verify this structure experimentally in comparison with the Litz wire coil. The result revealed that the proposed structure can have similar AC resistance and the similar height with the same surface area and the same number of turns. Moreover, the experimental result showed a possibility to further height reduction by optimization of the magnetic and winding isolation design. Consequently, the experiment supported practical effectiveness of the proposed structure for induction heating.**

Keywords— copper loss, foil wire, induction cooker, proximity effect.

I. Introduction

Recently, the induction heating is employed in many applications due to its advantages such as fast heating, high efficiency, cleanness, and safety. Particularly, the induction heating is widely utilized for the induction cookers. These cookers are commonly operated above 20kHz in order to suppress the acoustic noise. The operating frequency can reach further higher to approximately 100kHz for heating the pan of non-iron metals.

However, the high frequency operation may cause intense skin and proximity effects at the heating coil. These effects leads to concentration of the current distribution in the wire cross-section [1]–[7], generating large copper loss. Therefore, the heating coil is generally made of the Litz wire to suppress these effects [8]–[11].

The Litz wire is a special wire made of thin isolated wire strands. These strands have the far smaller dimension than the skin depth; and these strands are generally twisted or woven so that all of the strands pass all points of the cross-section of the Litz wire. Because of the symmetry of the electromagnetic condition among the strands, these strands carry the same current. Therefore, the Litz wire can achieve the uniform current distribution. As a result, the Litz wire is free from the skin and proximity effects and can suppress the copper loss.

However, the Litz wire tends to be expensive because of its complicated construction. In addition, the Litz wire coils may have large winding height due to low space factor of the Litz wire. Therefore, the solid copper wire is intensely required to replace the Litz wire for reduction of the cost and height of the heating coil because the solid copper wire tends to have simple construction and higher space factor than Litz wire.

Certainly, the solid copper wire tends to suffer from large copper loss in high frequency operation due to the skin and proximity effects. Therefore, a special magnetic structure suppressing the skin and proximity effects are essential for applications to the induction cookers. As a probable candidate of this magnetic structure, a novel heating coil structure of the copper foil, which is a thin solid copper wire, has been proposed in the previous study [12].

In this heating coil structure, a simple magnetic structure was employed to suppress the skin and proximity effects, as reviewed in the next section. In combination with this magnetic structure, the copper foil with the thickness less than the skin depth is wound to form the heating coil. As a result, the AC current is distributed uniformly inside the copper foil, thus reducing the copper loss.

This previous study discussed only the theoretical principle of this heating coil structure. Actually, this study has verified suppression of the skin and proximity effect, as well as resultant reduction of the copper loss only by the FEM analysis and in comparison with the thick solid rectangular copper wire. Therefore, experimental evaluation is needed to verify the effectiveness of this heating coil structure in comparison with the Litz wire heating coil.

The purpose of this paper is to verify the effectiveness of this proposed heating coil structure of the copper foil both by simulation and experiment. Section II briefly reviews the structure of the proposed structure and explains the theoretical principle how the skin and proximity effect can be suppressed in the structure. Then, section III presents the simulation and the experiment carried out to verify the effectiveness of the proposed structure. In addition, section presents an experiment which compares the copper loss between the proposed structure and the Litz wire heating coil.

II. Proposed Structure

Figure 1 shows the proposed heating coil structure with copper foil. The structure employs two strategies to suppress the inhomogeneity of the current distribution in vertical and horizontal directions respectively. One is that the wire thickness is designed to be less than the skin depth; the other is that the ferrite core is placed next to the wire edges. Below, the two strategies are explained.

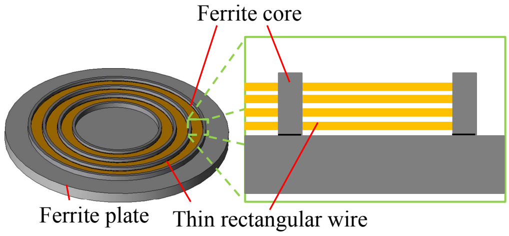


Fig.1 Proposed coil structure

A. Wire Thickness Smaller Than Skin Depth

First, the conventional problem of the solid copper wire is discussed with respect to the inhomogeneous current distribution in the vertical direction. For this purpose, we analyze the AC current distribution inside the thick solid copper wire. Figure 2 shows the cross section of the thick wire supplied with the high frequency AC current. The AC current is confined at the wire surface within the skin depth due to the skin effect. The skin depth δ is defined as following equation,

$$\delta = \sqrt{2\rho / \omega\mu} \tag{1}$$

where ρ is the resistivity of the material of the wire, μ is the permeability of the material of the wire and ω is the angular frequency.

We apply Ampere's law along the dotted line as shown Fig.2. Because the AC magnetic field does not penetrate the conductor through the skin depth, we can neglect the integration of the magnetic field along the top side of the dotted line. In addition, the integration of the magnetic field along the vertical sides can also be neglected because the magnetic field is perpendicular to the vertical sides. As a result, the integration of the magnetic field is contributed only by the bottom side, obtaining

$$\Delta I = H_s \tag{2}$$

where ΔI is the surface current per unit length and H_s is the surface magnetic field of the wire.

Equation (2) indicates that the surface current per unit length equals to the surface AC magnetic field. In other words, the AC current flowing the surface of wire is proportional to the surface magnetic field. Therefore, the surface magnetic field should be distributed uniformly for the uniform current distribution on the wire surface.

Now, we consider the heating coil of the solid rectangular wire with the thickness far greater than the skin depth, as shown in Fig. 3 (Left figure). This heating coil is constructed on the ferrite plate as is common in many practical heating coil to avoid the electromagnetic interference with the inverter, which is commonly disposed at the bottom of the heating coil.

The bottom wire surface of the lowest layer carries no AC current because the surface magnetic field is small due to large permeability of the ferrite plate. Therefore, all the AC current of the wire of the lowest layer flows in the top wire surface.

We apply again Ampere's law to the closed path passing through the center of the wire of the lowest layer and the center of the wire of the next layer, as shown in Fig. 3. Because the magnetic field vanishes inside the wire at the depth larger than the skin depth, the horizontal side of the closed path does not contribute to the integration of the magnetic field. In addition, the vertical side of the closed path does not also contribute the integration because the vertical side is perpendicular to the magnetic field. Therefore, no AC current must flow through the closed path, indicating that the bottom wire surface of the next layer carries the AC current flowing oppositely to but having the same amplitude as that of the top wire surface of the lowest layer. As a consequence, the top surface of the next layer must carry twice as large AC current as the top surface of the lowest layer.

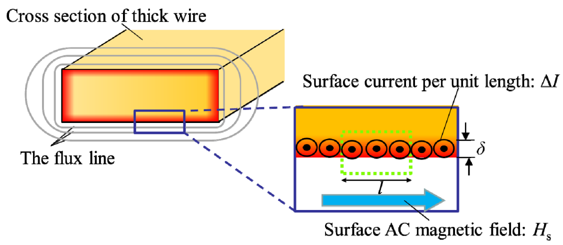


Fig.2 Cross section of thick wire

According to the similar discussion, the winding layer of the higher level must carry larger AC current at the bottom and top surfaces flowing in the opposite directions each other. This opposite AC current between the top and bottom surfaces tends to have much larger amplitude than the total AC current flowing in the wire, resulting in large copper loss.

In order to overcome this problem, the proposed structure employs the copper foil thinner than twice of the skin depth. As mentioned above, the AC current flows at the surface within the skin depth. Therefore, if the wire thickness is greater than twice of the skin depth, no AC current flows in the inner region of the wire; and therefore, the opposite current flows at the top and bottom surfaces without canceling each other. However, if the wire is thinner than twice the skin depth, the inner region of the wire also can carry the AC current and there the opposing current surface can cancel each other. This corresponds to suppressing the vertical inhomogeneity of the AC current distribution, which results in reduction of the copper loss.

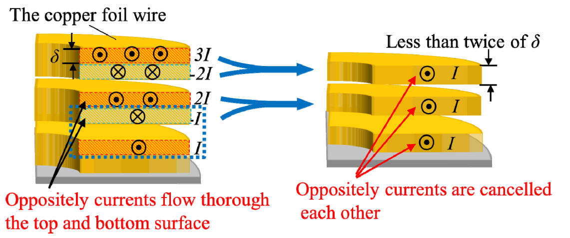


Fig.3 Strategy A for suppressing the vertical inhomogeneity of the AC current distribution

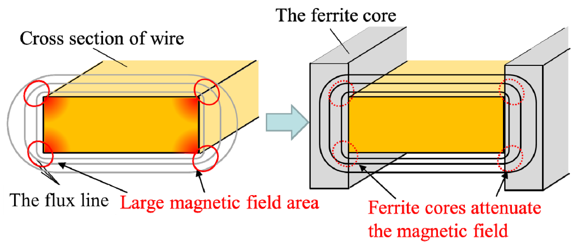


Fig. 4 Strategy B for suppressing the horizontal inhomogeneity of the AC current distribution

B. *Ferrite Core Wall at Wire Edge*

Next, the other strategy, which is the ferrite core is placed at the wire edge, is discussed to explain how it can dissolve the horizontal inhomogeneity of the AC current distribution [13].

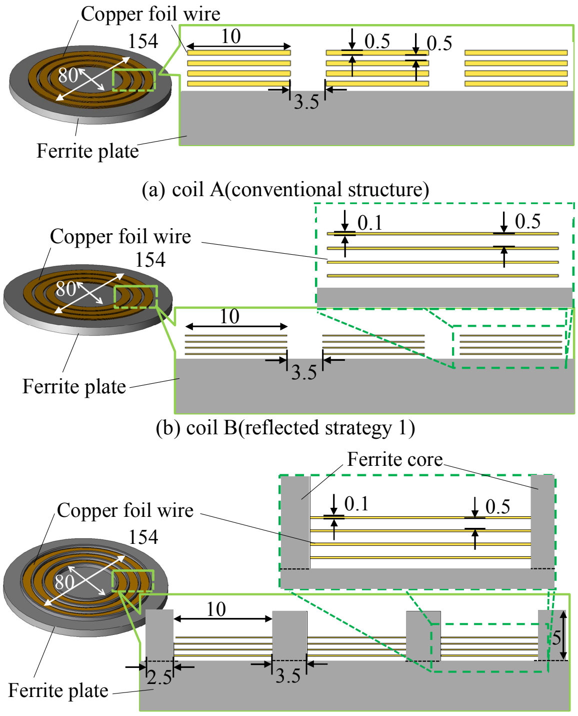
When the AC current flows through in the wire, the flux path is formed to surround the wire. As for the solid rectangular wire including the copper foil, the flux path curves at the wire edge. The curving flux path generally generates the inhomogeneity of the magnetic flux density because the inner side of the flux path is shorter than the outer side. As a result, the inner side has larger flux density than the outer side [14][15]. Consequently, intense magnetic field tends to occur near the wire edge. As discussed above, the AC current is distributed to be proportional to the surface magnetic field. Therefore, the AC current is concentrated at the wire edge, generating large copper loss.

In order to suppress this inhomogeneous AC current distribution at the wire edge, this strategy places vertical walls of the ferrite core in adjacent to the wire edge, as shown in Fig. 4. Ferrite can greatly reduce the magnetic field owing to its high permeability. Therefore, by covering the wire edge by the ferrite walls, the magnetic field at the wire edge can be reduced to avoid the AC current concentration at the wire edge.

III. Verification of Proposed Coil Structure

Simulation and experiment were carried out to verify that the proposed structure can reduce the copper loss. In order to verify the proposed structure, the AC resistance was compared among the three coils shown in Fig. 5. Photograph of the experimental prototype for coil C is presented in Fig. 6.

Coil A is the conventional coil structure with the solid rectangular wire, which has large cross sectional area to decrease the DC resistance. The wire thickness is designed to be far larger than the skin depth. On the other hand, Coil B is the coil structure with the copper foil, which is thinner wire than the skin depth. Hence, coil B employs only strategy A for suppressing the vertical inhomogeneity of the AC current distribution. Coil C is



(a) coil A(conventional structure)

(b) coil B(reflected strategy 1)

(c) coil C(reflected strategy 1 and 2)

Fig.5 The magnified view of three coils

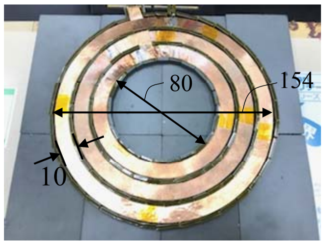


Fig.6 The coil C for the experimental verification of the proposed structure

TABLE I
Specifications of Three Coils

	Coil A	Coil B	Coil C
AC current		80kHz, 1Arms	
Number of turns [T]	12	12	12
Wire thickness [mm]	0.5	0.1	0.1
Insulation sheet thickness [mm]	0.5	0.5	0.5
Coil thickness [mm]	4	2.4	5

TABLE II
Materials of Three Coils

Component	Coil A	Coil B	Coil C
The copper foil	Hikari Corp. HC0526	Hikari Corp. HC133T	
The insulation sheet		Artec Corp. 20512	
Ferrite plate		FDK Corp. 6H60	
Ferrite core			Laird Corp. 33P2098-0M0

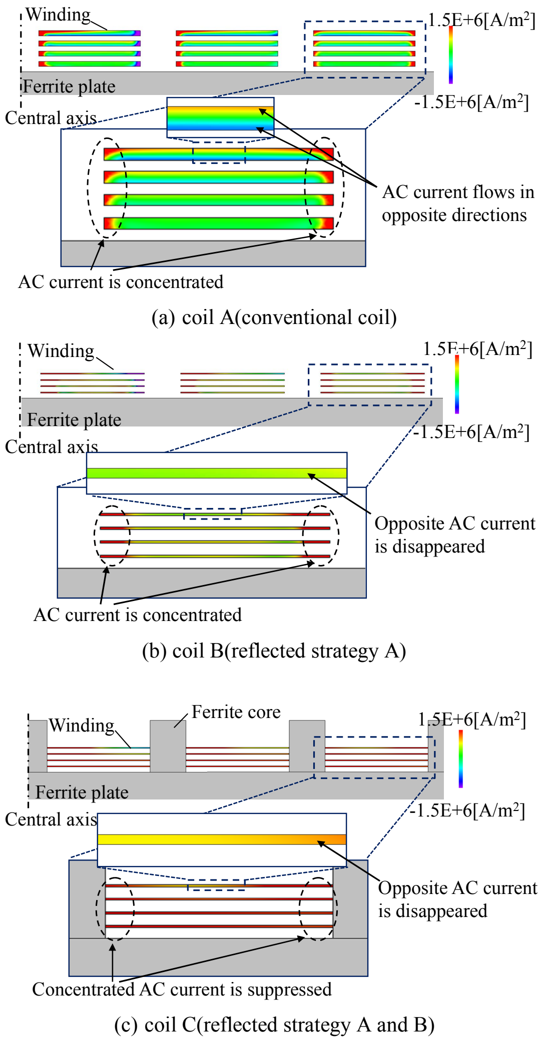


Fig. 7 Simulation result of current density distribution

the proposed structure with copper foil, which further has the ferrite core walls in adjacent to the wire edge in addition to coil B.

Table I and Table II show the specifications and materials of the prototypes. The coils were wound to have 12 turns with 4 winding layers on the ferrite plate. The outer and inner diameter of the coil is 154mm and 80mm . The width of copper foil is 10mm. The gap between the horizontally adjacent wires is 3.5mm. For the insulation between the vertically adjacent wires, the polypropylene sheets (Artec Corp. 20512) with thickness 0.05mm are inserted between the winding turns. Coil C has ferrite walls with the thickness of 5mm.

The AC current of 80kHz was applied to these coils. Therefore, the skin depth was 0.23mm. The wire thickness of the coil A was designed to be 0.5mm (approximately twice as large as the skin depth), whereas the wire thickness of coil B and coil C was designed to be 0.1mm (approximately a half of the skin depth).

Figure 7 shows the simulation result of current density distribution. Figure 8 shows the simulation and experiment results of the AC resistance. First, coil A and coil B were compared to verify the effectiveness of the strategy A. As shown in Fig. 7, opposite current flows

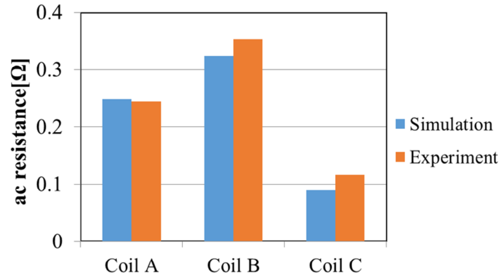


Fig. 8 The simulation and experiment result of ac resistance at 80kHz

between the top and bottom surface of the wire in coil A. Particularly, this opposite current flows intensely in the wire near the top of the winding, indicating the intense vertical inhomogeneity. Furthermore, the AC current was found to be concentrated at the wire edge, indicating the intense horizontal inhomogeneity.

This vertical inhomogeneity is suppressed in coil B, indicating the effectiveness of strategy A. However, the concentration of the AC current at the wire edge still remains in coil B. Because the thin wire reduced the cross-sectional area for the current flowing at the wire edge in coil B, the AC resistance of coil B was found to be larger than that of coil A, as can be seen in Fig. 8.

Next, coil B and coil C are compared to verify the effectiveness of strategy B. As seen Fig. 7, the AC current concentration at the wire edge was found to be successfully suppressed in coil C. As a result, the AC current is distributed more uniformly in coil C, resulting in reduction of the AC resistance. By suppressing the vertical and horizontal inhomogeneity, coil C exhibits the least AC resistance among the three coils. Particularly, coil C reduced the AC resistance by 52.2% compared with coil A, according to the experimental result.

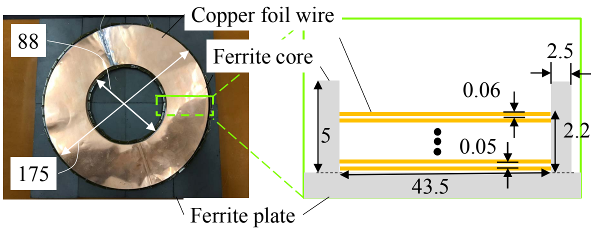
Figure 7 indicates that the proposed structure, i.e. coil C, can achieve uniform AC current distribution without using the Litz wire. Therefore, this result implies that the proposed structure can have similar AC resistance as the Litz wire coil but with higher space factor. In the next section, the proposed structure is compared with the Litz wire coil.

IV. Comparison between Proposed Structure Coil and Litz Wire Coil

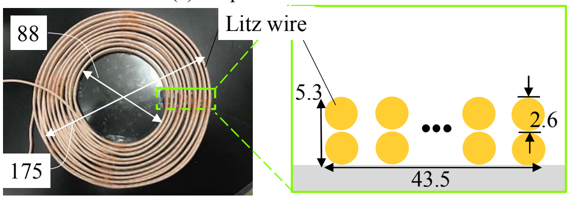
A. Prototype Design

The purpose of this section is to verify that the proposed structure can actually be utilized in replace of the Litz wire heating coil. Therefore, we designed the prototype of the proposed structure so that this prototype has the same number of turns and the same coil diameter as the prototype of the Litz wire heating coil.

The prototypes of the proposed structure and the Litz wire coil were shown in Fig. 9. Tabel III and Table IV show the specifications and materials of two heating coils. The outer and inner diameter of the coil was set at 175mm and 88mm respectively, excluding the ferrite core at wire edges. In addition, the number of turns of the coils



(a) Proposed structure coil



(b)Litz wire coil

Fig. 9 Prototype coil

TABLE III
SPECIFICATIONS OF EXPERIMENT

	Proposed structure	Litz wire
AC current	80kHz, 1Arms	
Number of turns [T]	20	20
Wire thickness [mm]	0.06	2.6
Wire width [mm]	43.5	2.6
Insulation sheet thickness [mm]	0.05	
Coil thickness [mm]	5	5.3

TABLE IV
THE COMPONENTS

Component	Proposed structure	Litz wire
The copper wire	Shim&gauge Corp. 10M×100×0.06	2UEWSTC
The insulation sheet	TGK Corp. 638-17-97-01	
Ferrite plate	FDK Corp. 6H60	
Ferrite core	Laird Corp. 33P2098-0M0	

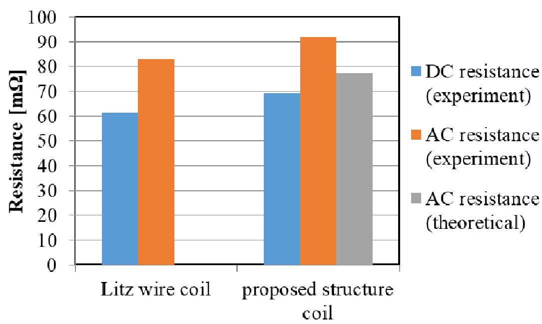


Fig.10 AC resistance

was set at 20. These coils were placed on the ferrite plate (FDK Corp., 6H60). The relative permeability of ferrite plate was 3000. The thickness of ferrite plate was 10mm.

The Litz wire employed for the prototype was 2UEWSTC. The diameter of the Litz wire was 2.6mm. The Litz wire incorporates 308 strands with the diameter of 0.1mm. This coil was designed to have two winding layers. As a result, the winding height of the Litz wire heating coil was 5.3mm.

On the other hand, the winding of the proposed structure was designed to have large width in order to make sufficiently large cross-section area of the copper foil. Therefore, the wire width the proposed structure has designed cover the whole coil area. As a result, the proposed structure has 20 winding layers.

The thickness of the copper foil was designed to minimize the AC resistance. In the proposed structure, the winding is located above the ferrite plate, and its edges adjacent to the ferrite core. Therefore, the magnetic field only exists at the winding layer and the space between the adjacent wires because the magnetic field into the high permeability material is very small. Furthermore, as mentioned at previous section, the flux line curves around the wire in the ferrite plate or ferrite core, and passes through straightly into the wire and space. Therefore, the magnetic field distribution is one-dimensional. Under this situation, the copper loss of proposed structure is calculated by one-dimensional analysis. The AC resistance of the proposed structure was calculated based on the theoretical analysis presented in [16]. According to this analysis, the AC resistance can be calculated using the one-dimensional electromagnetic field analysis according to the following equation:

$$R_{ac\_N} = \frac{R_{dc\_N}}{2}\frac{t}{\delta}\left[\frac{\sinh\left(\frac{t}{\delta}\right)+\sin\left(\frac{t}{\delta}\right)}{\cosh\left(\frac{t}{\delta}\right)-\cos\left(\frac{t}{\delta}\right)}+\frac{4N^2-1}{3}\frac{\sinh\left(\frac{t}{\delta}\right)-\sin\left(\frac{t}{\delta}\right)}{\cosh\left(\frac{t}{\delta}\right)+\cos\left(\frac{t}{\delta}\right)}\right] \quad (3)$$

where R_{ac_N} is the ac resistance of the coil, R_{dc_N} is the dc resistance of the coil, t is the wire thickness, δ is the skin depth, and N is the number of turns.

If the copper foil has excessively large thickness, the intense skin and proximity effects increases the AC resistance. If the copper foil has excessively small thickness, the wire does not have sufficient cross-sectional area for the AC current flow. Therefore, this case also increases the AC resistance. Consequently, there is the optimal thickness that minimize the AC resistance.

This optimal thickness can be determined by differentiating (3) with respect to the wire thickness t. As for the prototype of the proposed structure, the optimal thickness was determined as 68μm, given δ=0.23mm and N=20. Therefore, we employed the copper foil with the thickness of 60μm for constructing the prototype of the proposed structure. For the insulation between the vertically adjacent wires, the insulation sheets (TGK Corp. 638-17-97-01) with thickness 0.05mm which is made of PTFE are inserted between the winding turns.

The proposed structure has the ferrite walls that covers the outer and inner edge of the copper foil wire to suppress the horizontal inhomogeneity of the AC current distribution. The height of ferrite cores was set at 5.0mm, which determined the total height of the coil. Accordingly, the proposed structure reduced the winding height by 6% compared with the Litz wire coil.

Certainly, in this experiment, the proposed structure had similar height as the Litz wire coil. However, the height of the proposed structure was determined by the ferrite wall, which was designed to be sufficiently high to cover the whole winding, which is only 2.2mm high. Therefore, the net winding height is much reduced in the proposed structure. If the ferrite wall is optimized to reduce the height, the proposed structure probably exhibits effective reduction in height, which will be elucidated in the future study.

B. AC Resistance Measurement

The AC resistance of the prototypes were measured using the LCZ meter (NF Corp., NF2340). Figure 10 shows the experiment results of the AC resistance at 80kHz. The AC resistance of the proposed structure coil was slightly larger than that of Litz wire coil, although both of the prototypes exhibited the similar values for the AC resistance.

Consequently, the prototype of the proposed structure was found to have the similar height as well as the similar AC resistance as the prototype of the Litz wire coil. This indicates that the proposed structure can replace the Litz wire heating coil, suggesting the effectiveness of the proposed structure.

In this paper, the ferrite walls and the ferrite plate were implemented separately. However, in the manufacturing process, these ferrite elements can be integrated into one piece because the ferrite is commonly produced by the mold. This may probably reduce the cost of implementing the additional ferrite walls.

V. CONCLUSION

The Litz wire has been commonly utilized for the heating coils for the induction heating. However, the comparatively complicated construction as well as the low space factor of the Litz wire leads to high cost and large winding height of the heating coil. In order to mitigate these drawbacks, this paper investigated the feasibility of the recently proposed heating coil structure with the copper foil winding.

This paper verified the effectiveness of this structure by simulation and experiment. As a result, this structure was found to suppress the skin and proximity effect without utilizing the Litz wire. Owing to this attractive feature, the proposed structure reduced the AC resistance compared with the heating coil of the solid rectangular wire. In addition, comparison of the prototype heating coils between the proposed structure and the Litz wire coil revealed that the proposed structure can have similar AC resistance and similar height. The results supported that the proposed structure can replace the Litz wire heating coil. The results also suggested that optimization of the ferrite wall may further reduce the height of the proposed structure, which will leads to the effective reduction of the heating coil using the proposed structure.

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