Title

Reduction of eddy current loss in magnetoplated wire

Abstract

Purpose

The purpose of this study is to reduce eddy current loss in a wire that is affected by an alternating field passing through it. This allows us to upgrade the efficiency of transformers and to increase the quality factor in coils.

Design/methodology/approach

We propose the use of a magnetoplated wire (MPW) to reduce eddy current loss in a wire. An MPW is a copper wire (COW) whose circumference is plated with a magnetic thin film. In additional, the theoretical equation for eddy current loss in an MPW is derived for ease of analysis.

Findings

We calculate the eddy current loss in an MPW as a function of the relative permeability and resistivity of its magnetic thin film to reduce the resistance due to the proximity effect of a coil. The eddy current loss in an MPW whose magnetic thin film has a relative permeability of 500 and a resistivity of 0.12 μΩm can be reduced to 4 % that of COW at a frequency of 1 MHz.

Originality/value

The use of MPW can be expected to upgrade the efficiency of transformers and to increase the quality factor in coils.

Paper type

Research paper

Title
Reduction of eddy current loss in magnetoplated wire

Keywords
Magnetoplated wire, Eddy current loss, Relative permeability, Resistivity, Theoretical equation, Magnetic thin film

Title

Reduction of eddy current loss in magnetoplated wire

Full paper

1. Introduction

Copper loss must be reduced to upgrade the efficiency of transformers and to increase the quality factor in coils (Lavers and Bolborici, 1999; Acero *et al.*, 2005; Mizuno, Enoki, Hayashi *et al.*, 2007). For this purpose, it is necessary to reduce the AC resistance that contributes to most of the coil resistance in the high-frequency range over 100 kHz. The AC resistance, which is due to both the skin effect and the proximity effect, is controlled by the proximity effect. The proximity effect is caused by the alternating field made by the current flowing in wires of a coil. The copper loss caused by the proximity effect corresponds to the eddy current loss in a wire.

We proposed the use of a magnetoplated wire (MPW) to reduce eddy current loss in a wire. An MPW is a copper wire (COW) whose circumference is plated with a magnetic thin film (Yoshimura *et al.*, 1994). The characteristics of MPW are that it (a) increases inductance, (b) provides more magnetic flux, and (c) reduces AC resistance (Mizuno, Enoki and Hayashi *et al.*, 2007). (a) and (b) are due to the relative permeability of the magnetic thin film being larger than that of COW. (c) is due to alternating fields generated by nearby wires passing through the magnetic thin film, which has larger values of relative permeability and resistivity than copper (Mizuno, Enoki and Asahina *et al.*, 2007).

The finite element method (FEM) using a personal computer is generally used for magnetic field analysis. However, the number of elements of a coil with MPW becomes enormous because the thickness (1 μm) of the magnetic thin film of MPW is thin. Thus, the use of FEM causes a problem in that the analysis time is long and there is a memory capacity restriction.

In this paper, we derive the theoretical equation for the eddy current loss in an MPW that is affected by the alternating field passing through it for ease of analysis. The validity of the theoretical equation is examined, and it is compared with the result of FEM. The analysis confirms that eddy current loss in an MPW is reduced in comparison with that in a COW. In addition, we examine the effect of the physical properties (frequency, alternating field, thickness, relative permeability and resistivity) of the magnetic thin film of MPW on eddy current loss. In this paper, we discuss the following.

1. Derivation of theoretical equation of eddy current loss in an MPW
2. Effect of the physical properties of magnetic thin film on eddy current loss

2. Structure of wire

Figure 1 shows the structures of COW and MPW. The COW is a copper wire whose diameter is 90 μm. The MPW has a copper wire whose diameter is 90 μm and is plated with a magnetic thin film. The thickness of the magnetic thin film is 1 μm. The Fe and NiFe thin films are used as a magnetic thin film to reduce eddy current loss. The Fe thin film has a relative permeability of μ_{r2} = 100 and a resistivity of ρ_2 = 0.098 μΩm. The NiFe thin film has a μ_{r2} = 500 and a ρ_2 = 0.12 μΩm.

"Take in Figure 1"

3. Derivation of theoretical equation of eddy current loss in an MPW

Figure 2 shows the model for deriving the theoretical equation for eddy current loss in an MPW. An MPW has a length of infinity, and it is a plated copper wire whose radius is r_1 with a magnetic thin film whose thickness is $r_2 - r_1$. We derive the theoretical equation of eddy current loss observed when an alternating field at frequency f is applied perpendicularly to the wire.

"Take in Figure 2"

First, the differential equation for the copper wire and magnetic thin film is derived in order to obtain the theoretical equation of eddy current loss in an MPW. Next, general solutions for each region are derived from the differential equation. The coefficient of general solutions is required to set boundary conditions for magnetic field strength and flux density on the boundary surface. Finally, the theoretical equation of eddy current loss in an MPW can be obtained using the general solutions.

Maxwell's equations and Ohm's law are respectively defined as follows:

$$\mathrm{rot}\ \boldsymbol{H} = \boldsymbol{J} \quad (\mathrm{A/m^2}) \tag{1}$$

$$\mathrm{rot}\ \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \quad (\mathrm{V/m^2}) \tag{2}$$

$$\boldsymbol{J} = \frac{\boldsymbol{E}}{\rho} \quad (\mathrm{A/m^2}) \tag{3}$$

where: H – magnetic field strength (A/m), J – current density (A/m^2), E – electric field strength (V/m), B – flux density (T), ρ – resistivity (Ωm).

The vector potential A is defined by equation (4) using the magnetic field strength for ease of analysis (Lammeraner and Stafl, 1964). We employ a coulomb gage that exhibits equation (5):

$$\boldsymbol{H} = \mathrm{rot}\, \boldsymbol{A} \quad \text{(A/m)} \tag{4}$$

$$\mathrm{div}\, \boldsymbol{A} = 0 \quad \text{(A/m)} \tag{5}$$

The vector potential A only has a z direction component, and it is a function of r and φ direction components. The differential equation given by equation (4) is substituted into one of Maxwell's equations and Ohm's law, and the result is given by equations (6) and (7) (Mclachlan, 1954):

$$\frac{\partial^2 A}{\partial r^2} + \frac{1}{r}\frac{\partial A}{\partial r} + \frac{1}{r^2}\frac{\partial^2 A}{\partial \varphi^2} - \mathrm{j}k^2 A = 0 \quad \text{(A/m}^2\text{)} \tag{6}$$

$$k^2 = \frac{\omega\mu}{\rho} \quad (\mathrm{m}^{-2}) \tag{7}$$

where: φ – the angle (rad) made with the magnetic field, ω – angular frequency (rad/s), μ – permeability (H/m).

The general solution of the differential equation shown in equation (6) is broken down into the solutions in (a) the copper wire ($0 \le r \le r_1$), (b) magnetic thin film ($r_1 \le r \le r_2$), and (c) air ($r \ge r_2$). The vector potentials A_1, A_2 and A_3 of each region are given as follows (Lammeraner and Stafl, 1964).

(a) Copper wire ($0 \le r \le r_1$)

$$A_1 = C_1 \mathrm{J}_1(\mathrm{j}^{3/2} k_1 r) \sin\varphi \quad \text{(A)} \tag{8}$$

$$k_1{}^2 = \frac{\omega\mu_1}{\rho_1} \quad (\mathrm{m}^{-2}) \tag{9}$$

$$\mu_1 = \mu_{\mathrm{r1}}\mu_0 \quad \text{(H/m)} \tag{10}$$

where: C_1 – coefficient (A), J_n – Bessel function of the first kind of order n, ρ_1 – resistivity (Ωm) of Cu, μ_{r1} – relative permeability of Cu, μ_0 – permeability (H/m) of vacuum.

(b) Magnetic thin film ($r_1 \le r \le r_2$)

$$A_2 = \left\{ C_2 \mathrm{J}_1(\mathrm{j}^{3/2} k_2 r) + B_2 \mathrm{K}_1(\mathrm{j}^{1/2} k_2 r) \right\} \sin\varphi \quad \text{(A)} \tag{11}$$

$$k_2{}^2 = \frac{\omega\mu_2}{\rho_2} \quad (\mathrm{m}^{-2}) \tag{12}$$

$$\mu_2 = \mu_{\mathrm{r2}}\mu_0 \quad \text{(H/m)} \tag{13}$$

where: C_2, B_2 – coefficients (A), K_n – modified Bessel function of the second kind of order n, ρ_2 – resistivity (Ωm) of the magnetic thin film, μ_{r2} – relative permeability of the magnetic thin film.

(c) Air ($r \ge r_2$)

$$A_3 = \sqrt{2} H r \sin\varphi + \frac{C_3}{r}\sin\varphi + K \quad \text{(A)} \tag{14}$$

where: C_3 – coefficient (Am), K – integration constant (A).

The magnetic field strength and flux density in each region are derived using the vector potential required to solve the differential equation. The boundary conditions of magnetic field strength and flux density are applied on the boundary surface of MPW. There are two boundary surfaces, namely, Cu – Fe thin film and Fe thin film – Air, and the boundary conditions are respectively given by equations (15), (16), (17) and (18):

$$H_{1\varphi}\big|_{r=r_1} = H_{2\varphi}\big|_{r=r_1} \quad \text{(A/m)} \tag{15}$$

$$\mu_1 H_{1r}\big|_{r=r_1} = \mu_2 H_{2r}\big|_{r=r_1} \quad \text{(T)} \tag{16}$$

$$H_{2\varphi}\big|_{r=r_2} = H_{3\varphi}\big|_{r=r_2} \quad \text{(A/m)} \tag{17}$$

$$\mu_2 H_{2r}\big|_{r=r_2} = \mu_0 H_{3r}\big|_{r=r_2} \quad \text{(T)} \tag{18}$$

where: H_φ and H_r – φ and r direction components of the magnetic field strength (A/m).

The coefficients of the general solution are obtained using the boundary conditions and simultaneous equations (Lammeraner and Stafl, 1964). In the appendix, the coefficients C_1, C_2, B_2 and C_3 are showed.

The eddy current density that is affected by an alternating field is deduced using the vector potential in each region. The eddy current densities of copper wire, J_1 ($0 \le r \le r_1$), and magnetic thin film, J_2 ($r_1 \le r \le r_2$), are respectively given by equations (19) and (20):

$$J_1 = \mathrm{j}\frac{k_1{}^2 A_1}{\sqrt{2}} \quad \text{(A/m}^2\text{)} \tag{19}$$

$$J_2 = \mathrm{j}\frac{k_2{}^2 A_2}{\sqrt{2}} \quad \text{(A/m}^2\text{)} \tag{20}$$

The eddy current loss that affects the alternating field is deduced using the eddy current density in each region. The eddy current loss per unit length in an MPW, P_e, is given by the sum of the eddy current loss per unit length in copper wire, P_{e1}, and that in magnetic thin film, P_{e2}:

$$P_e = P_{e1} + P_{e2}$$
$$= \frac{\rho_1}{2}\int_0^{2\pi}\int_0^{r_1} |J_1|^2 r\, \mathrm{d}r\mathrm{d}\varphi + \frac{\rho_2}{2}\int_0^{2\pi}\int_{r_1}^{r_2} |J_2|^2 r\, \mathrm{d}r\mathrm{d}\varphi \quad \text{(W/m)} \tag{21}$$

This equation can be expanded for composite plating wire to derive the general solution for multiple regions and boundary conditions.

4. Effect of the physical properties of magnetic thin film on eddy current loss

Figure 3 shows a comparison of eddy current losses in MPW and COW as a function of frequency. We compare the eddy current loss under an alternating field of 1 kA/m obtained using the theoretical equation and that obtained by FEM. The theoretical equation of eddy current loss in an MPW is calculated using equation (21). The eddy current loss in a COW, P_e, is given by equation (22) (Lammeraner and Stafl, 1964). However, the eddy current density in a COW, J_1, and coefficient C_1 are given by equations (19) and (23), respectively:

$$P_e = \frac{\rho_1}{2}\int_0^{2\pi}\int_0^{r_1} |J_1|^2 r\, \mathrm{d}r\mathrm{d}\varphi \quad \text{(W/m)} \tag{22}$$

$$C_1 = \frac{4\sqrt{2}\,\mu_0 H r_1}{\mathrm{j}^{3/2}\mu_0 k_1 r_1 \left\{ \mathrm{J}_0(\mathrm{j}^{3/2}k_1 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_1 r_1)\right\} + 2\mu_1 \mathrm{J}_1(\mathrm{j}^{3/2}k_1 r_1)} \quad \text{(A)} \tag{23}$$

The structures of MPW and COW are shown in Figure 1. The difference of the results based on the theoretical equation and FEM was 2.5 %, at maximum. The eddy current loss in an MPW whose Fe thin film has a relative permeability of μ_{r2} = 100 and a resistivity of ρ_2 = 0.098 μΩm was reduced to 24 %, from 11 mW/m to 2 mW/m, that in COW at f = 1 MHz. Also, the eddy current loss in an MPW whose NiFe thin film has a relative permeability of μ_{r2} = 500 and a resistivity of ρ_2 = 0.12 μΩm was reduced to 4 %, from 11 mW/m to 0.4 mW/m, that in COW at f = 1 MHz. Therefore, the eddy current loss in MPW can be reduced to a greater extent than in COW.

"Take in Figure 3"

Figure 4 shows a comparison of eddy current losses in MPW and COW as a function of alternating field. We compare the eddy current loss under a frequency of 1 MHz obtained theoretically using equations (21) and (22). The eddy current loss at H = 1 kA/m yielded the same results, figure 1. The eddy current loss increased with increasing alternating field passing through a wire.

"Take in Figure 4"

Figure 5 shows the eddy current loss in an MPW as a function of relative permeability and resistivity. The eddy current loss in MPW decreased with increasing relative permeability and resistivity of the magnetic thin film. It causes the eddy current loss in the copper wire to be reduced because of the alternating field passing through the magnetic thin film.

"Take in Figure 5"

Figure 6 shows a comparison of eddy current losses in MPW and COW as a function of the thickness of the magnetic thin film. The MPW has a copper wire whose diameter is 90 μm and the thickness of the magnetic thin film is changed. The eddy current loss in MPW with a 3 μm thick Fe thin film was 1.5 mW/m, at minimum. The eddy current loss in MPW with a NiFe thin film that is 1.3 μm thick was 0.43 mW/m, at minimum.

"Take in Figure 6"

The resistance of a coil increases, thereby generating eddy current loss in the conductor that is subjected to the alternating field made by an approaching conductor (proximity effect). Thus, it is possible to reduce the increase in AC resistance, because MPW can reduce the eddy current loss (Mizuno *et al.*, 2006).

5. Conclusion

5.1 Derivation of theoretical equation of eddy current loss in an MPW

We derived the theoretical equation for eddy current loss in an MPW. The eddy current losses derived using the theoretical equation and FEM are in good agreement (within a difference of 2.5 %), thereby confirming the validity of the theoretical equation. The effect of the physical properties of a magnetic thin film on eddy current loss obtained using the theoretical equation can be more easily calculated than that obtained by FEM.

5.2 Effect of the physical properties of magnetic thin film on eddy current loss

The eddy current loss in an MPW whose Fe thin film has a relative permeability of μ_{r2} = 100 and a resistivity of ρ_2 = 0.098 μΩm can be reduced to 25 % that in COW. In addition, that in an MPW whose NiFe thin film has a relative permeability of μ_{r2} = 500 and resistivity of ρ_2 = 0.12 μΩm can be reduced to 4 % that in COW.

The efficiency of transformers and the quality factor in coils can be expected to increase because the use of MPW can reduce the increase in the AC resistance caused by the proximity effect.

Appendix

The coefficients C_1, C_2, B_2 and C_3 are given by equations (24), (25), (26) and (27):

$$C_1 = \frac{2\sqrt{2}\,\mu_0\mu_2 H k_2\left[\mathrm{j}^{3/2}\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_2 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_2 r_1)\right\}\mathrm{K}_1(\mathrm{j}^{1/2}k_2 r_1) + \mathrm{j}^{1/2}\mathrm{J}_1(\mathrm{j}^{3/2}k_2 r_1)\left\{\mathrm{K}_0(\mathrm{j}^{1/2}k_2 r_1) + \mathrm{K}_2(\mathrm{j}^{1/2}k_2 r_1)\right\}\right]}{r_2 \cdot \mathit{\Delta}} \ \mathrm{(A)} \tag{24}$$

$$C_2 = \frac{2\sqrt{2}\,\mu_0 H\left[\mathrm{j}^{3/2}\mu_2 k_1\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_1 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_1 r_1)\right\}\mathrm{K}_1(\mathrm{j}^{1/2}k_2 r_1) + \mathrm{j}^{1/2}\mu_1 k_2\mathrm{J}_1(\mathrm{j}^{3/2}k_1 r_1)\left\{\mathrm{K}_0(\mathrm{j}^{1/2}k_2 r_1) + \mathrm{K}_2(\mathrm{j}^{1/2}k_2 r_1)\right\}\right]}{r_2 \cdot \mathit{\Delta}} \ \mathrm{(A)} \tag{25}$$

$$B_2 = \frac{-2\sqrt{2}\,\mathrm{j}^{3/2}\mu_0 H\left[\mu_2 k_1\mathrm{J}_1(\mathrm{j}^{3/2}k_2 r_1)\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_1 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_1 r_1)\right\} - \mu_1 k_2\mathrm{J}_1(\mathrm{j}^{3/2}k_1 r_1)\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_2 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_2 r_1)\right\}\right]}{r_2 \cdot \mathit{\Delta}} \ \mathrm{(A)} \tag{26}$$

$$\begin{aligned}
C_3 = \frac{1}{\mathit{\Delta}} \times \Bigg[& \mathrm{j}^{3/2}\left[\mu_2 k_1\mathrm{J}_1(\mathrm{j}^{3/2}k_2 r_1)\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_1 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_1 r_1)\right\} - \mu_1 k_2\mathrm{J}_1(\mathrm{j}^{3/2}k_1 r_1)\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_2 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_2 r_1)\right\}\right] \\
& \times\left[-\frac{\sqrt{2}}{2}\mathrm{j}^{1/2}\mu_0 H k_2 r_2\left\{\mathrm{K}_0(\mathrm{j}^{1/2}k_2 r_2) + \mathrm{K}_2(\mathrm{j}^{1/2}k_2 r_2)\right\} - \mu_2 H\mathrm{K}_1(\mathrm{j}^{1/2}k_2 r_2)\right] \\
& + \left[-\mathrm{j}^{3/2}\mu_2 k_1\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_1 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_1 r_1)\right\}\mathrm{K}_1(\mathrm{j}^{1/2}k_2 r_1) - \mathrm{j}^{1/2}\mu_1 k_2\mathrm{J}_1(\mathrm{j}^{3/2}k_1 r_1)\left\{\mathrm{K}_0(\mathrm{j}^{1/2}k_2 r_1) + \mathrm{K}_2(\mathrm{j}^{1/2}k_2 r_1)\right\}\right] \\
& \times\left[\frac{\sqrt{2}}{2}\mathrm{j}^{3/2}\mu_0 H k_2 r_2\left\{\mathrm{J}_0(\mathrm{j}^{1/2}k_2 r_2) - \mathrm{J}_2(\mathrm{j}^{1/2}k_2 r_2)\right\} - \mu_2 H\mathrm{J}_1(\mathrm{j}^{1/2}k_2 r_2)\right]\Bigg] \ \mathrm{(Am)}
\end{aligned} \tag{27}$$

$$\mathit{\Delta} = \begin{vmatrix}
-\mathrm{j}^{3/2}k_1\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_1 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_1 r_1)\right\} & \mathrm{j}^{3/2}k_2\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_2 r_1) - \mathrm{J}_2(\mathrm{j}^{3/2}k_2 r_1)\right\} & -\mathrm{j}^{1/2}k_2\left\{\mathrm{K}_0(\mathrm{j}^{1/2}k_2 r_1) + \mathrm{K}_2(\mathrm{j}^{1/2}k_2 r_1)\right\} & 0 \\
\mu_1\mathrm{J}_1(\mathrm{j}^{3/2}k_1 r_1) & -\mu_2\mathrm{J}_1(\mathrm{j}^{3/2}k_2 r_1) & -\mu_2\mathrm{K}_1(\mathrm{j}^{1/2}k_2 r_1) & 0 \\
0 & \frac{1}{2}\mathrm{j}^{3/2}k_2\left\{\mathrm{J}_0(\mathrm{j}^{3/2}k_2 r_2) - J_2(\mathrm{j}^{3/2}k_2 r_2)\right\} & -\frac{1}{2}\mathrm{j}^{1/2}k_2\left\{\mathrm{K}_0(\mathrm{j}^{1/2}k_2 r_2) + \mathrm{K}_2(\mathrm{j}^{1/2}k_2 r_2)\right\} & \frac{1}{{r_2}^2} \\
0 & \mu_2\mathrm{J}_1(\mathrm{j}^{3/2}k_2 r_2) & \mu_2\mathrm{K}_1(\mathrm{j}^{1/2}k_2 r_2) & -\frac{\mu_0}{r_2}
\end{vmatrix} \ (\mathrm{H}^2/\mathrm{m}^5). \tag{28}$$

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Figure

Figure 1 Structures of COW and MPW (unit: μm).

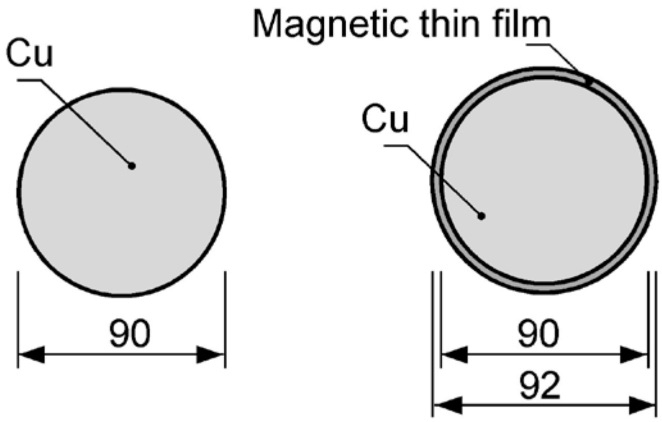


Figure 2 Model for deriving the theoretical equation for eddy current loss in MPW.

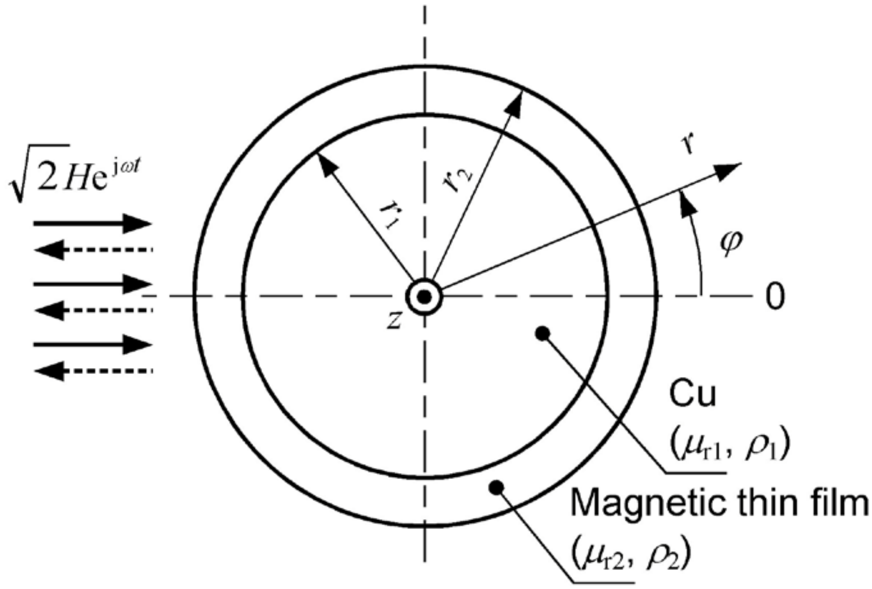


Figure 3 Comparison of eddy current losses in MPW and COW as a function of frequency (H = 1 kA/m, Cu: μ_{r1} = 0.999991, ρ_1 = 0.0172 μΩm, MPW (Fe thin film): μ_{r2} = 100, ρ_2 = 0.098 μΩm, MPW (NiFe thin film): μ_{r2} = 500, ρ_2 = 0.12 μΩm).

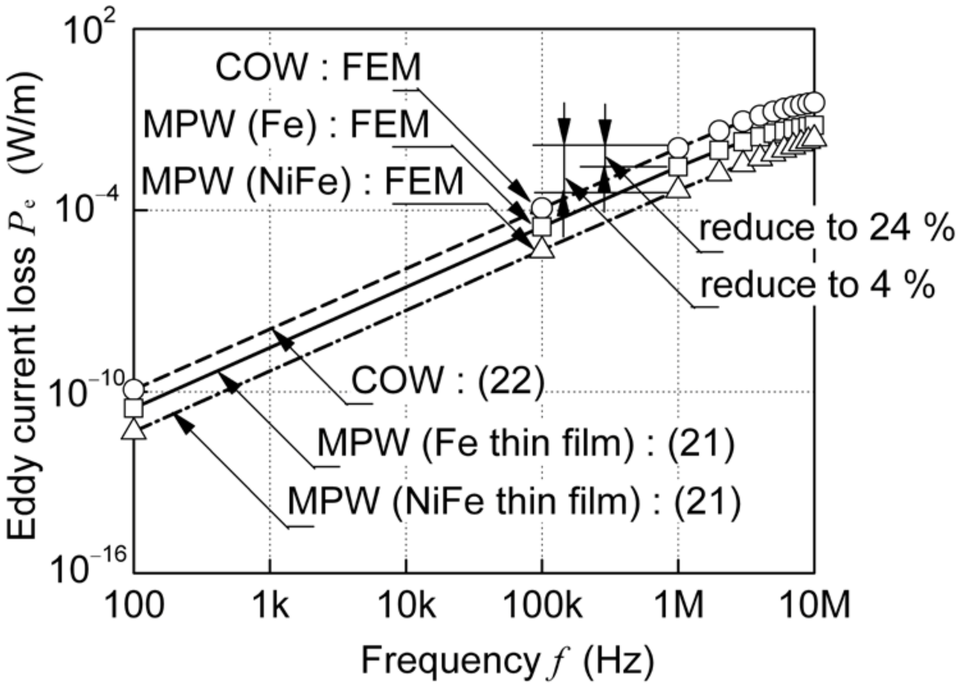


Figure 4 Comparison of eddy current losses in MPW and COW as a function of alternating field (f = 1 MHz, Cu: μ_{r1} = 0.999991, ρ_1 = 0.0172 μΩm, MPW (Fe thin film): μ_{r2} = 100, ρ_2 = 0.098 μΩm, MPW (NiFe thin film): μ_{r2} = 500, ρ_2 = 0.12 μΩm).

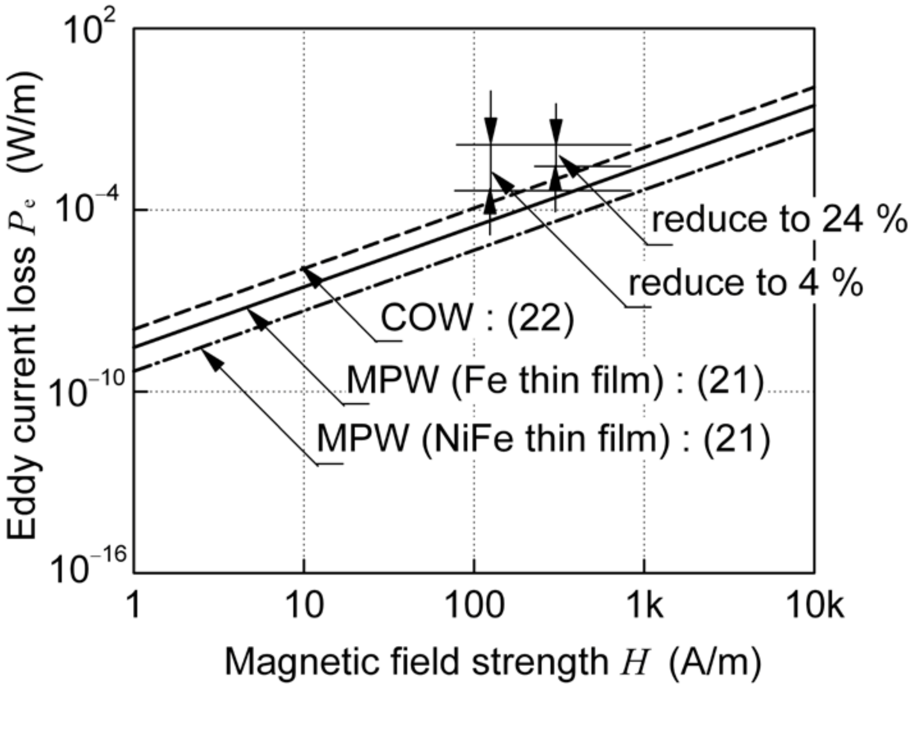


Figure 5 Eddy current loss in MPW as a function of relative permeability and resistivity (H = 1 kA/m, f = 1 MHz, Cu: μ_{r1} = 0.999991, ρ_1 = 0.0172 μΩm, MPW (Fe thin film): μ_{r2} = 100, ρ_2 = 0.098 μΩm, MPW (NiFe thin film): μ_{r2} = 500, ρ_2 = 0.12 μΩm).

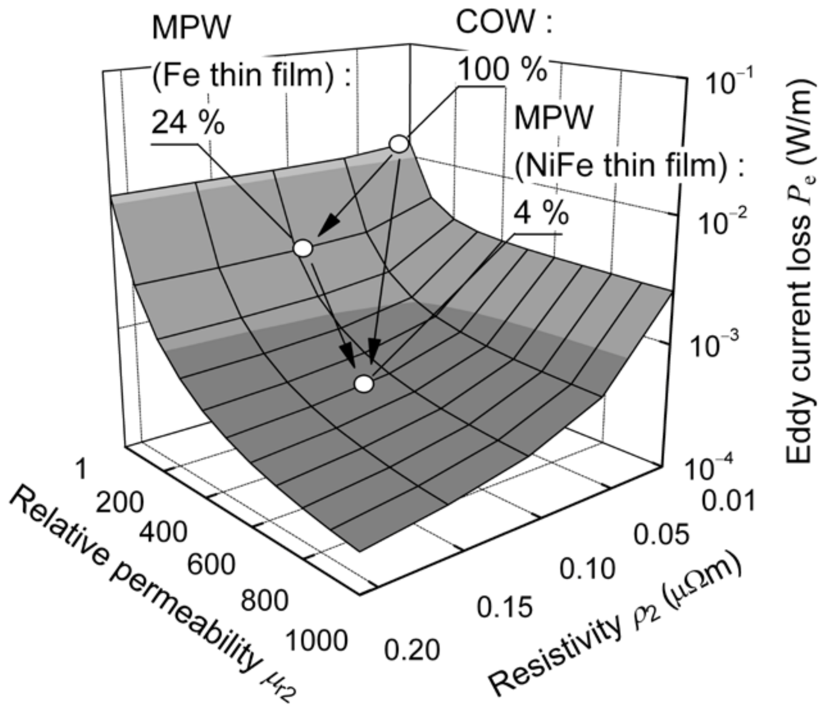
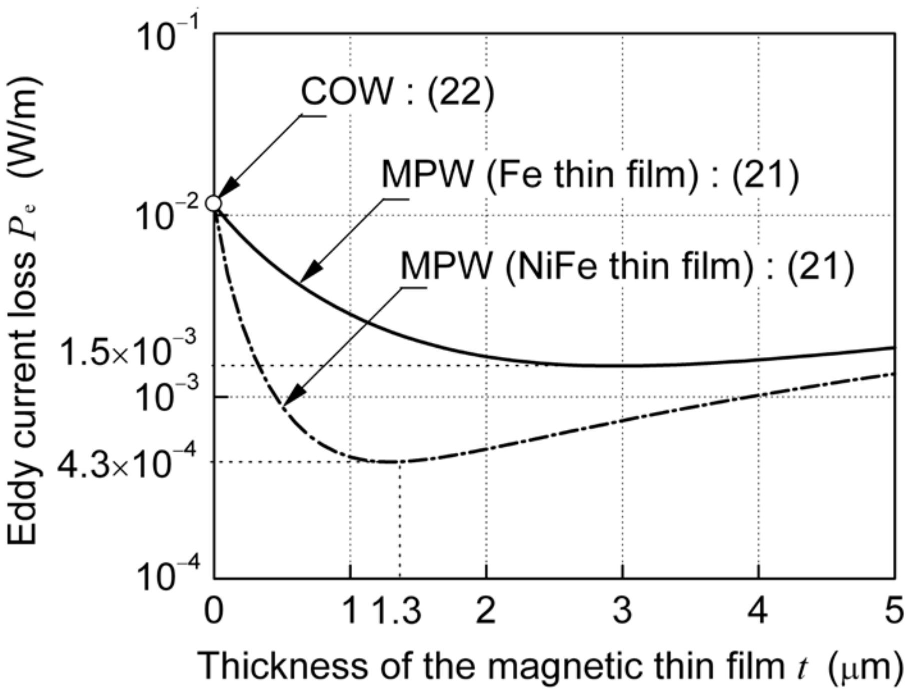


Figure 6 Comparison of eddy current losses in MPW and COW as a function of thickness of the magnetic thin film (r_1 = 45 μm, H = 1 kA/m, f = 1 MHz, Cu: μ_{r1} = 0.999991, ρ_1 = 0.0172 μΩm, MPW (Fe thin film): μ_{r2} = 100, ρ_2 = 0.098 μΩm, MPW (NiFe thin film): μ_{r2} = 500, ρ_2 = 0.12 μΩm).



COW : (22)
MPW (Fe thin film) : (21)
MPW (NiFe thin film) : (21)
10−1
10−2
1.5×10−3
10−3
4.3×10−4
10−4
Eddy current loss Pe (W/m)
0
1
1.3
2
3
4
5
Thickness of the magnetic thin film t (μm)

Author: Tsutomu Mizuno

Author: Shigemi Enoki

Author: Takayuki Suzuki

Author: Takashi Asahina

Author: Masahiro Noda

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