IMPACT OF MATERIAL PROPERTY VARIATIONS AND SENSOR POSITIONING ON THE COATING THICKNESS DETERMINATION OF STEEL SHEETS

DOI
https://doi.org/10.18690/um.feri.4.2025.36

ISBN
978-961-286-986-1

MARTIN KOLL,[1] DANIEL WÖCKINGER,[1] CHRISTOPH DOBLER,[1] GERD BRAMERDORFER,[1] GEREON GOLDBECK,[1] STEFAN SCHUSTER,[2] STEFAN SCHEIBLHOFER,[2] NORBERT GSTÖTTENBAUER,[2] JOHANN REISINGER[2]

[1] Johannes Kepler University Linz, Institute of Electric Drives and Power Electronics, Linz, Austria
martin.koll@jku.at, daniel.woeckinger@jku.at, christoph.dobler@jku.at, gerd.bramerdorfer@jku.at, gereon.goldbeck@jku.at
[2] Voestalpine Stahl GmbH, Linz, Austria
stefan.schuster2@voestalpine.com, stefan.scheiblhofer@voestalpine.com, norbert.gstoettenbauer@voestalpine.com, johann.reisinger@voestalpine.com

This paper deals with investigations to determine the layer thickness of electrically conductive coatings on electrically conductive and ferromagnetic steel substrates. For this purpose, an eddy current sensor system with well-known analytical model for ideal conditions is used. Based on this, different coil setups are examined and compared with regard to sensor positioning. A robustness analysis against parameter fluctuations is carried out.

Keywords:
Eddy current testing,
coating thickness determination,
FE simulation,
analytical modeling,
nonlinear effects

University of Maribor Press

I Introduction

In industry, it is often necessary to apply a coating to steel sheets to protect them against external influences that may damage the material, e.g., corrosion. In order to ensure the quality of these coatings, it is necessary to be able to accurately determine its thickness. According to the literature, an X-ray gauge is often used to determine coating thicknesses [1]. This method is typically expensive and poses problems in terms of occupational safety. For this reason, an eddy current coil system is used in this paper [2]. In the real world, however, parameter fluctuations, edge effects, noise and other undesirable influences have significant impact on the achievable measurement accuracy. The aim of this paper is to analyze these effects and to indicate their impact on the coating thickness determination.

II Methodology

In this work, a coil system consisting of a cylindrical excitation coil and two measuring coils, as shown in Fig. 1 is analyzed. For the analytical model of this arrangement, it is assumed that there is a coated steel sheet close by to the coil. The coating is non-magnetic and the substrate underneath is a ferromagnetic material, both are electrically conductive. The mutual impedance of this arrangement yields [2]

$$\begin{aligned}\zeta = &\frac{j\omega\mu_0\pi N_1 N_2 \bar{r}}{(r_2-r_1)(r_4-r_3)L_2L_6}\int_0^\infty \frac{1}{\alpha^6} J(r_2,r_1)J(r_4,r_3)e^{-2\alpha L}\left(e^{-\alpha(L_2-2L_5-L_6)}-1\right)\\ &\times\left(e^{-\alpha L_5}-e^{-\alpha(L_6+L_5)}\right)\left(e^{-\alpha L_2}-1\right)\\ &\times\frac{(\alpha+\beta_1)(\beta_1-\beta_2)+(\alpha-\beta_1)(\beta_1+\beta_2)e^{2\alpha_1 c}}{(\alpha-\beta_1)(\beta_1-\beta_2)+(\alpha+\beta_1)(\beta_1+\beta_2)e^{2\alpha_1 c}}\,d\alpha. \end{aligned} \tag{1}$$

Here ω is the angular excitation frequency, N_1 and N_2 are the number of turns of the excitation coil and the measuring coil, r_i and L_i are the dimensions of the respective coil and

$$\bar{r} = \frac{r_1+r_2}{2}, \tag{2}$$

$$\beta_i = \frac{1}{\mu_i}\sqrt{\alpha + j\bar{r}^2\omega\mu_0\mu_i\sigma_i}, \;(3) \tag{3}$$

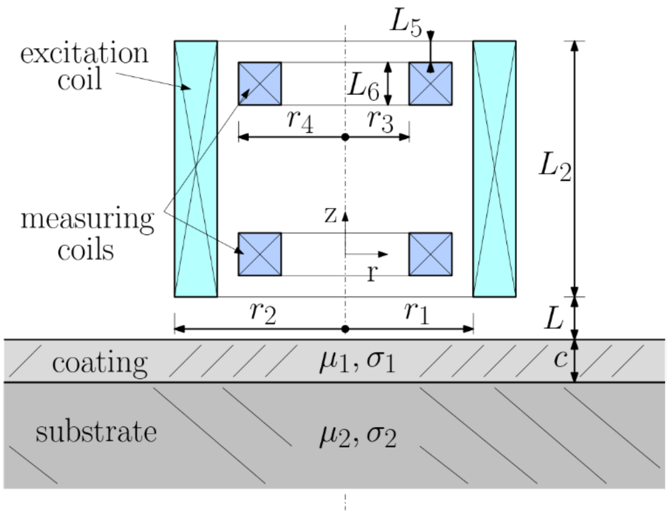

Figure 1: Drawing of Differential coil model setup with dimensioning.

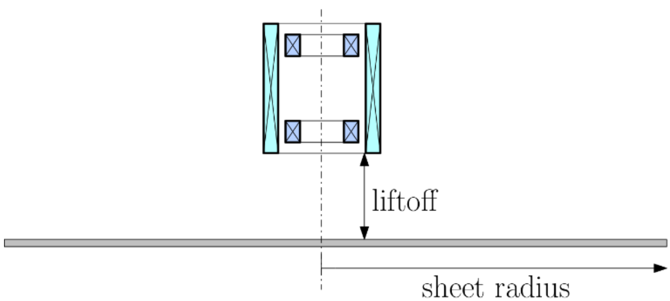

Figure 2: Sketch of the simulation setup for the analysis of the edge effect via variation of the sheet radius.

$$\alpha_i = \sqrt{\alpha + \mathrm{j}\overline{r^2}\omega\mu_0\mu_i\sigma_i}, \tag{4}$$

$$\frac{1}{\alpha^2}\int_{x=\alpha r_1}^{\alpha r_2} x J_1(x)\,\mathrm{d}x = \frac{1}{\alpha^2} J(r_2, r_1), \tag{5}$$

with $J_1(x)$ a Bessel function of first kind and order. The relative permeability and the conductivity of the layers are μ_i and σ_i. Due to process conditions, e.g. temperature and position fluctuations of the sheet metal to be measured, it is required to position the measuring coils to be relatively far away from the specimen. In an FEA-simulation the validity of the analytical model is evaluated and the mesh rules found in [3] are extended for larger air gaps of more than 20 mm. The software FEMM [4] is used for this purpose. In an industrial plant, the assumption of an infinite extension certainly does not apply. For this reason, different coil setups, shown in Tab. 1, are examined and the edge effect as a function of the air gap is analyzed via sheet radius variations shown in Fig. 3, to determine the minimum distance of the sensor from the edge of the sheet to to exclude the influence of boundary effects.

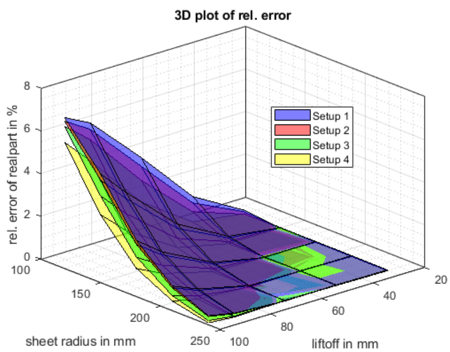

Figure 3: Relative error when comparing FEA and analytical model depending on the sheet radius and the air gap between sheet and coil.

The following applies to the investigations carried out:

$N_1 = 43$, $N_2 = 18$, $\sigma_1 = 15$ MS/m, $\sigma_2 = 5$ MS/m, $\mu_2 = 500$, $c = 10$ µm. In Fig. 3 the real part of the mutual impedance ζ of the analytical model is compared with that of the FEA simulation.

Table 1: Analyzed Coil Setups

	Setup 1	Setup 2	Setup 3	Setup 4
r1 [mm]	25	13	25	10
r2 [mm]	26	14	26	11
r3 [mm]	22	10	22	7
r4 [mm]	24	12	24	9
L2 [mm]	40	40	20	10
L5 [mm]	2.85	2.85	2.85	1.5
L6 [mm]	4.1	4.1	4.1	3

Furthermore, the analytical model is used to perform a robustness analysis with respect to parameter fluctuations. As shown in [3], the coating conductivity σ_1 must be known exactly in order to determine the thickness of the coating. The influence of a parameter change in the coating conductivity of $\pm$ 20 % on the mutual impedance curve at different operating points is shown in Fig. 4. It can be seen that with a small coating thickness and high relative permeability of the steel substrate, the influence of a coating conductivity variation on the mutual impedance is the most significant.

Measurements are carried out on a test bench shown in Fig. 5. This test bench is used to measure various sheet metal samples with different coating thicknesses between 6 µm and 24 µm and different air gaps between 1.5 mm and 20 mm.

III Outlook

The final paper will provide measurement data. The behaviour of different coating thicknesses for the same steel substrate with different air gaps is investigated. The results will be useful for the industrial use of this type of sensor to determine the thickness of coatings on steel sheets.

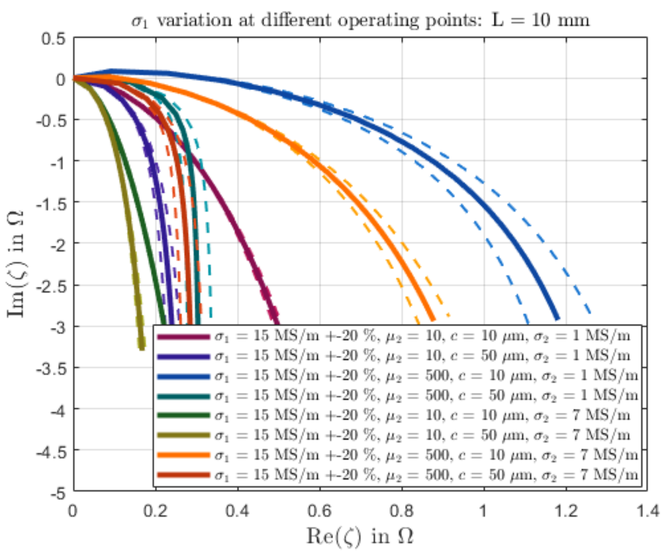

Figure 4: Effect of ±20% coating conductivity variation on the mutual impedance curve.

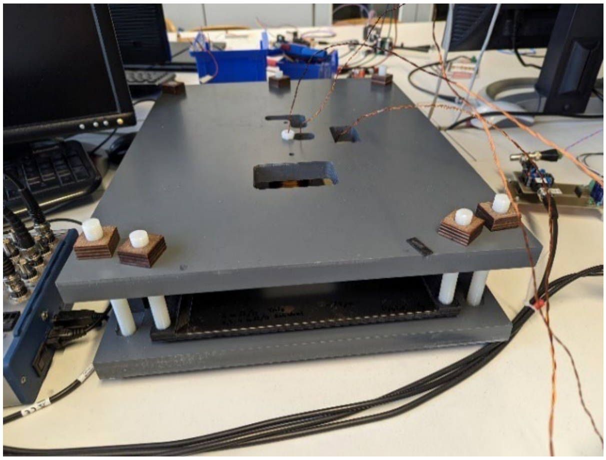

Figure 5: Test bench for measuring sheet metal samples.

Acknowledgment

This work has been supported by the COMET-K2 ”Center for Symbiotic Mechatronics” of the Linz Center of Mechatronics (LCM) funded by the Austrian federal government and the federal state of Upper Austria .

References

[1] Moriyasu, Keisuke, Daigo Kosaka, Kazuhiko Kakishita, Mitsuo Hashimoto, und Fumio Koyama. „Measurement of Plating Thickness with High Liftoff Using Eddy Current Testing“. Electromagnetic Non-Destructive Evaluation (XXI), 2018, 263–68. https://doi.org/10.3233/978-1-61499-836-5-263.

[2] Dodd, Deeds, Luquire; Spoeri. Some Eddy-Current Problems and Their Integral Solutions. Oak Ridge National Laboratory, 1969.

[3] Koll Martin, Daniel Wöckinger, Christoph Dobler, Gereon Goldbeck, Gerd Bramerdorfer, Stefan Schuster, Stefan Scheiblhofer, Norbert Gstöttenbauer, und Johann Reisinger. „Investigations on eddy current sensors regarding inline-capability of zinc coating monitoring using a model-based estimator“. Journal of Magnetism and Magnetic Materials, 2024, https://doi.org/10.1016/j.jmmm.2024.171754.

[4] Meeker, David. "Finite element method magnetics." FEMM 4.32 (2010): 162.