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Simulation, Manufacturing and Evaluation of a Transformer Eddy-Current Sensor for Deep-Drawing Processes

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Summary:
This article shows the manufacturing and evaluation of an eddy current sensor based on the transformer principle for monitoring a deep drawing process. First, the optimized parameters of two inductive sensor coils were determined by 2D-finite-element simulation (conductive path width, number of turns, measurement frequency) concerning the resulting output voltage. Then, the sensor was fabricated according to the simulation using thin film technology processes. Finally, the sensor is evaluated and a comparison with the simulation is shown.

Keywords: deep drawing, eddy current sensor, inductive sensor, thin film technology, transformer

Introduction

For monitoring the material flow of the deep-drawing process, the use of eddy current sensors is one of the most suitable choices due to their non-contact measurement method. Two types of eddy current sensors can be used, one consisting of only one coil (parametric principle) and the other consisting of two coils (transformer principle). Recent work already presented a parametric micro planar sensor coil on a stainless-steel substrate using thin film technology [1]. Since the substrate is used to protect the coils by installing the sensor upside down, the sensitivity of the sensor decreases [1]. To improve the induced output signal, the optimized sensor parameters should be determined by means of an electromagnetic simulation. Thereafter, certain modifications of the thin film manufacturing process are required. In this article, a transformer is used, due to its simplification of the measurement and evaluation of the induced voltage compared to the inductance in the parametric principle [2]. Finally, the sensor is evaluated against simulation results.

Simulation-based Design

The 2D models applied for finite-element simulation with the software Ansys Electronics are depicted in Fig. 1. Two opposing planar coils (excitation and measuring coil) with the same outer d_o and inner d_i diameters – for optimal interconnection of the coils while forming the flux – were chosen. z_1 and z_2 are the insulating layers between the substrate and the secondary coil and the secondary and primary coils, which are 25 µm and 10 µm, respectively. z_3 represents the distance between the substrate and the sheet which is 10 µm, due to the anti-wear layer and lubricants used in the deep drawing process. The model depth in z-direction is determined to 55 mm. When a constant current (0.5 A) is applied to the excitation coil (primary coil), the induced voltage is read on the measuring coil (secondary coil) during deep drawing.

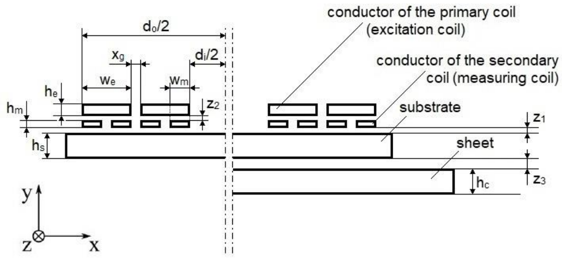

Fig. 1. 2D-illustration of the sensor used for simulation without (left) and with (right) sheet

To conclude the sensor sensitivity, the ratio between U_S and U_0 should be determined, where U_S is the voltage induced on the secondary coil fully covered with the sheet and U_0 is its induced voltage without any sheet. For higher sensor sensitivity, the ratio U_S/U_0 should deviate as much as possible from 1. Therefore, the influencing parameters to maximize the signal are investigated. According to the simulation, an increase in the number of turns of the primary coil leads to an increase in the voltage induced on the secondary coil, while U_S/U_0 remains constant. The number of turns of the secondary coil is kept at 25 (based on previous work [1]). 5 is chosen as the number of turns of the primary coil. Furthermore, if the difference between the outer and inner diameter of the coils is decreased, resulting in a denser arrangement of the conductors, the absolute change of induced voltage is increased [1]. Therefore, the distance between the conductors x_g is reduced to 50 µm to have denser coils with the same number of turns. Lengthening the coils outer diameter d_o increases the absolute change of the induced voltage [1]. However, to measure narrow areas accurately, d_o should be as small as possible without significantly decreasing the sensitivity. Therefore, a compromise should be made. In this case, we decided for more precision and decreased d_o to 15 mm, while d_i is 5.1 mm. Other selected parameters are presented in Table 1.

Tab. 1: Parameters of the optimized transformer sensor based on simulation (see Fig. 1)

Symbol	Value	Symbol	Value
h_e	15 µm	h_c	1 mm
h_m	5 µm	w_e	150 µm
h_s	1 mm	w_m	950 µm

Sensor Fabrication

A 25 µm insulating layer z_1 of photosensitive polyimide LTC 9320 (Fujifilm) is spin-coated onto a 1 mm thick 4” stainless steel (1.4301) wafer. For galvanic deposition of the conductors, a seed layer is sputtered consisting of 50 nm chromium as an adhesion promoter and 200 nm copper. The 5 µm thick copper conductors h_m of the secondary coil are electroplated onto the seed layer using a photomask and the resist AZ® 10xt. Then the 10 µm thick VIAs of the coil are further electroplated. Afterwards, the photomask is removed and the seed layer is eliminated by ion beam etching and the conductors and VIAs are embedded in a 15 µm thick polyimide. Thereafter, all the processes are repeated for the primary coil, where the thickness of the conductors h_e is now 15 µm and therefore the polyimide embedding thickness is 25 µm. The VIAs of the secondary coil are further electroplated in each subsequent step. Finally, conductive connections to 4 VIAs are made by 10 µm thick copper electroplating, and the entire sensor is protected by embedding in a 25 µm thick polyimide layer. The processed sensor has a size of about 65 mm x 15 mm and is shown in Fig. 2.

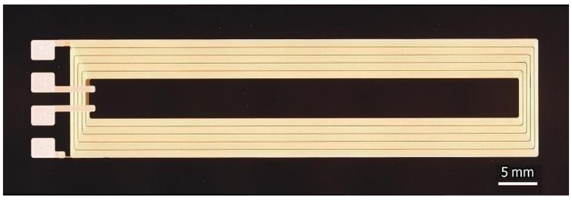

Fig. 2. Top view of the fabricated microsensor in transformer configuration

Measurement Results

To test the manufactured sensor and evaluate its sensitivity, the induced voltage on the secondary coil by applying a current of 0.5 A to the primary coil was measured at different frequencies, once U_0 and once U_S with an austenitic 1 mm thick steel sheet. To compare the measurement results with the simulation results, the ratio U_S/U_0 for simulation and measurement was plotted in Fig. 3. Both graphs are almost parallel and have a maximum sensitivity of 19 % at a frequency of 40 kHz, with the ratio U_S/U_0 showing a lower sensitivity in the experiment. The difference between the results of the simulation and the experiment could be due to the simplified model of the simulation e.g., the missing coil ends.

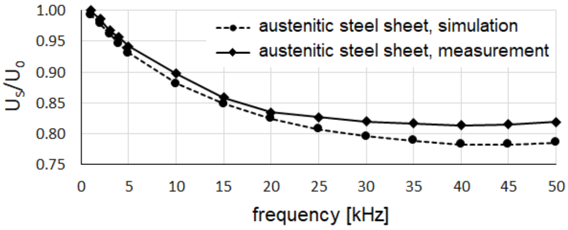

Fig. 3. Comparison of simulated and measured U_S/U_0-curves

Conclusion

An eddy current sensor for monitoring of the deep-drawing process based on the transformer principle was designed and manufactured according to optimized parameters based on 2D-finite-element simulation. The sensor was fabricated using photolithography, electrodeposition of copper and polyimide embedding. It was evaluated for two extreme cases (completely covered with an austenitic steel sheet and a completely free sensor) with different frequencies. The ratio between the induced voltage of the two measured cases showed a maximum sensitivity of 19 % at a frequency of 40 kHz. Furthermore, a comparison between the simulation and measurement results showed a similar course. Further investigations include other sheet materials and sensor protection against wear to use multiple sensors simultaneously in a deep-drawing machine.

References

[1] M. Arndt, F. Dencker and M. C. Wurz, Novel Eddy-Current Sensor for Industrial Deep-Drawing Applications, *IEEE Sensors* (2019); doi: 10.1109/SENSORS43011.2019.8956948

[2] V. Seidemann, S. Buttgenbach, Closely Coupled Micro Coils with Integrated Flux Guidance: Fabrication Technology and Application to Proximity and Magnetoelastic Force Sensors, *IEEE Sensors Journal* 3, 615-621 (2003); doi: 10.1109/JSEN.2003.817172