DOI 10.5162/SMSI2023/D1.4

Multifrequency Multichannel Eddy Current Sensor System for the Analysis of Mechanical States in Ferromagnetic Materials

Frank Wendler[1], Robert Laue[2], Sebastian Härtel[3], Olfa Kanoun[1], Birgit Awiszus[2]
[1] Professorship Measurement and Sensor Technology, Chemnitz University of Technology, Reichenhainer Str. 70, 09126 Chemnitz, Germany
[2] Professorship Virtual Production Engineering, Chemnitz University of Technology, Reichenhainer Str. 70, 09126 Chemnitz, Germany
[3] Chair of Hybrid Manufacturing, Brandenburg University of Technology, Konrad-Wachsmann-Allee 17, 03046 Cottbus, Germany
frank.wendler@etit.tu-chemnitz.de

Summary:
In this work, we introduce the concept of a multifrequency multichannel eddy current sensor for the contactless simultaneous measurement of distance, relative magnetic permeability, the magnitude of magnetic anisotropy, angle of magnetic anisotropy, the magnitude of tilting, and direction of tilting. The System is demonstrated at a sample in a tensile test experiment.

Keywords: inductance spectroscopy, anisotropy measurement, permeability measurement, in-process measurement, material characterization

Introduction

Eddy current sensors have been already successfully applied in the field of material testing and the quantitative analysis of distance and electric and magnetic properties. Most sensor application focus on a few dominant use cases like the measurement of the distance and conductivity, when other influences are neglected or compensated. Concepts for the simultaneous measurement of multiple measurands are still subject to recent research and are challenged by the problem of effect separation. Especially the analysis of magnetic material properties could open access to several hard-to-measure quantities if the individual contribution could be isolated and quantified. The magnetic properties of ferromagnetic material depend on factors such as mechanical stress, defect density, grain size, and other changes in microstructure.

In the field of metal forming variable factors are defect density and mechanical stress, while the others can be considered constant. The increase in defects in the crystal structure reduces the ability of the material to magnetize and adjust to external magnetic fields. Mechanical stress does change the magnetic properties over the so-called Villari Effect depending on the direction of the stress. This results in stress-induced magnetic anisotropy in the material. Since both influences are expected to mutually affect each other, the novel introduced sensor approach aims at the simultaneous characterization of both effects and mutual correction. For this purpose, a multifrequency approach for the simultaneous measurement of distance and relative magnetic permeability is combined with the tilting compensated measurement of the magnetic anisotropy.

Structure of Sensor

The sensor consists of a central excitation coil and 8 angular aligned receiving coils displayed in fig. 1. The central coil can be excited at various frequencies in the range of 5 kHz to 1 MHz.

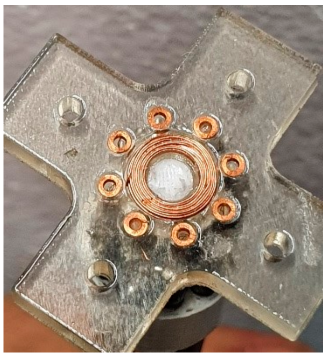

Fig. 1. Sensor head of the multisensor system with central excitation coil and 8 angular receiving coils

For each frequency current and the voltage are measured in amplitude and phase. This information can be used to calculate the spectra of the inductance of the central coil and is the foundation for the calculation of the distance and the magnetic permeability. The eight receiving coils along the circumference of the excitation coil analyze the magnitude of the excitation field for angular variations resulting from material anisotropy.

Analysis of Distance and Magnetic Permeability

The distance and the electric and magnetic properties have a characteristic influence on the shape of the spectra of the sensor inductance. In general, the inductance is enhanced at low frequencies by the magnetic properties of ferromagnetic material and reduced at high frequencies by the eddy current effect in the material. The magnitude of this change does mainly depend on the distance. In between the high and the low-frequency case is the region where the sensor inductance does drop for increasing frequencies. The position of this region does mainly depend on the ratio between the electric conductivity and magnetic permeability. This characteristic behavior is used in combination with an eddy current model [1] and an implemented particle filter to obtain the values of the relative magnetic permeability and the distance from one spectrum of the inductance [2].

Analysis of Magnetic Anisotropy and Correction of Tilting

The obtained amplitudes of the voltages of the eight receiving coils are analyzed over a Fast Fourier Transform along the angular coordinate. Tilting does create a sine signal with one maximum and one minimum over 360° because one side of the sensor coil will get closer to the target and one side will get further away. The magnetic anisotropy will create a sine signal with two maxima and two minima over 360°. A frequency selective analysis can separate and quantify the contribution of tilting and magnetic anisotropy and analyze the respective direction.

Experimental Evaluation

The sensor system was attached to the sample of DC01 steel in a tensile test experiment. The sample was elongated 30 mm at a constant speed and then relieved in four steps of the remaining force. The loading starts at about 50 s and results in a strong increase of anisotropy (blue curve) and a strong decrease in magnetic permeability (orange curve) in figure 2. The elongation continues until 350 s. In this phase, anisotropy increases to the maximum and then decreases, which correlates with the stress in the sample. The permeability decreases to a nearly constant level. The sample remains on stationary condition till 430 s at an elongation of 30 mm while permeability and anisotropy maintain stable. Then the remaining force is relieved in four steps till the 700 seconds mark. The steps are clearly visible in the blue curve of the anisotropy, but the step height is not uniform and increases with decreasing load. For the permeability and increase is observable for the unloading cycle.

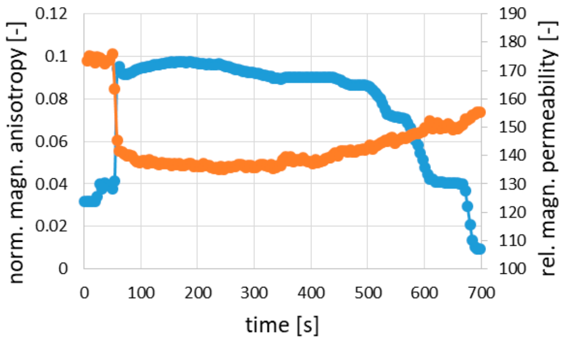

Fig. 2. Observed curves of magnetic anisotropy (blue) and relative permeability (orange) during a tensile test experiment of the DC01 steel sample

Conclusions

The multisensor system does allow the non-contact measurement of magnetic permeability and magnetic anisotropy with the compensation of the geometric influences of tilting and distance variations. The combination of two sensor concepts and measurement effects does not only allow the measurement at one spot. It creates the opportunity to mutually compensate geometric effects and isolate the origin of changes in the magnetic properties. For the investigated sample the responses of magnetic permeability and magnetic anisotropy were highly correlated but reveal characteristic differences in the detailed view. This is a necessary foundation for the separation of the underlying causes.

Acknowledgement

The authors would like to thank the German Research Foundation for funding the project (project number 424334154) within the framework of SPP2183: Property Controlled Forming Processes.

References

[1] Dodd, C. V., and W. E. Deeds. "Analytical solutions to eddy-current probe-coil problems." *Journal of applied physics* 39.6, 2829-2838 (1968); doi: 10.1063/1.1656680

[2] Lu, Mingyang, et al. "Reducing the lift-off effect on permeability measurement for magnetic plates from multifrequency induction data." IEEE Transactions on Instrumentation and Measurement 67.1,167-174 (2017); doi: 10.1109/TIM.2017.2728338