DOI 10.5162/SMSI2023/A6.3

Quantum Magnetometry for Material Testing

Kerstin Thiemann[1], Andreas Blug[1], Alexander Bertz[1]
[1] Fraunhofer Institute for Physical Measurement Technologies IPM, 79110 Freiburg, Germany,
kerstin.thiemann@ipm.fraunhofer.de

Summary:
Optically pumped zero-field magnetometers (OPM) are extremely sensitive to small variations in magnetic stray fields. However, their spatial resolution limits their application in non-destructive test-ing. With the help of flux guides these challenges can be overcome. This paper shows an example how the combination of OPM and flux guide can be used to measure magnetic stray fields of partial penetration weld seams in ferromagnetic steel sheets from the bottom side.

Keywords: Quantum sensing, non-destructive testing, magnetic testing, ferromagnetic materials

Introduction

Residual stresses are one of the major issues in welded parts since they could be detrimental to the integrity of components and structure [1]. Within ferromagnetic materials, these stresses alter the local magnetization and therefore the external magnetic field of the component [2, 3]. As magnetometers measure the average change of magnetization in a measurement volume, highly sensitive and commercially available quantum sensors like optically pumped magnetometers (OPM) measuring magnetic field B in a vapor cell are promising candidates for non-destructive testing with small measurement volumes or high spatial resolution [4].

In fatigue trials on mesoscale ferritic steel specimen with a loaded volume of about 0.1 mm³, the external magnetic field changed by about 5 nT when mechanical stress was altered from negative to positive yield stress [5, 6]. In principle, the sensitivity of the sensor of 15 fT/√Hz [7] would be sufficient to measure stress concentrations prior to crack initiation. However, the measurement volume inside the component and therefore the lateral spatial resolution at the surface of OPM sensors are limited by the physical distance between component surface and the vapor cell inside the sensor to several millimeters. To overcome this problem, Kim and Savukov used flux guides from Mn-based ferrites to measure the lateral component of the magnetic field with high spatial resolution [8].

In this paper, we use a different flux guide geometry measuring the normal component of the external magnetic field. This geometry should be appropriate for NDT of ferromagnetic components with high relative permeability μ_r as their magnetic stray field is refracted towards the normal at the surface. At the example of two neighboring weld seams, we demonstrate the improvement of the lateral spatial resolution compared to a OPM sensor only.

Material and Methods

A sketch of the experimental setup is shown in Fig. 1. A conically shaped flux guide (relative permeability μ_r = 2300) is attached to the OPM with the aid of a 3D printed housing and placed into a magnetic shielding via the top opening. The horizontal axis is externally motorized and carries the sample. All components are placed in such a way that the point of measurement is in the center of the magnetic shielding and the sample moves along the flux guide.

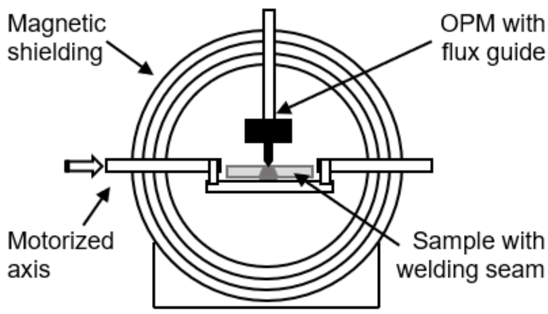

Fig. 1. Sketch of setup: inside the magnetic shielding on the vertical axis a OPM is placed where a flux guide can be attached. The horizontal axis is externally motorized and holds the sample.

The sample shown in Fig. 2 consists of two partial penetration welding seams which are 4 mm apart, attaching a second layer of ferromagnetic steel [9]. To show the effects of the flux guide, measurements are performed with just the OPM and the with the OPM flux guide combination. The sample is moved with

0.1 mm/s and the sampling frequency of the OPM is 200 Hz. The distance d between sample surface and point of measurement are kept as small as possible (d < 1 mm, excluding the distance from the housing to the center of the vapor cell within the OPM).

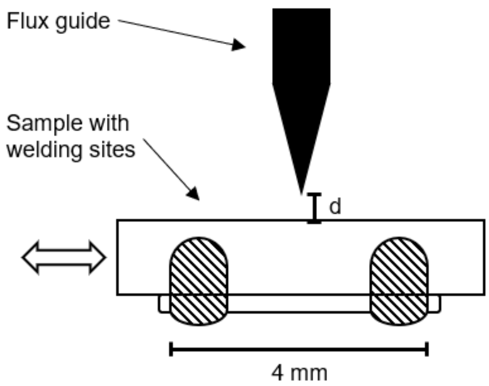

Fig. 2. Detailed sketch of the sample with two partial penetration welding seams spaced 4 mm apart. The sample is moved in a distance d along flux guide to measure magnetic stray fields from the bottom side.

Results

The comparison between the measurements with only the sensor (blue) and the combination of OPM and flux guide (red) is shown in Fig. 3. The sample has a magnetic gradient across the scanned line. However, the location of the welding sites (indicated in grey pattern) are only clearly visible in the measurements including the flux guide.

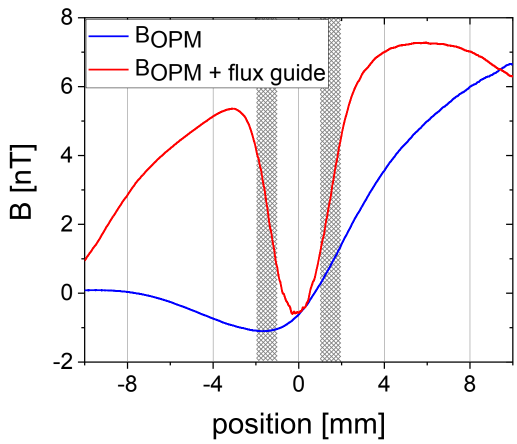

Fig. 3. Comparison of the two measurements using OPM only (blue) and using the OPM with the flux guide attached (red). The changes of the magnetic field (B) on the surface of the sample across a welding site (grey patterned).

Conclusion and outlook

This works illustrates that the use of a flux guide significantly enhances the spatial resolution of OPM. The spatial resolution is very dependent on the distance between the vapor cell inside the OPM sensor and the measurement site. Implementing a flux guide simplifies to control spatial resolution and measurement volume in the sample. In this respect, significant progress by optimizing the geometry of the flux guide is expected.

Further research on the geometry, material and hysteresis behavior of flux guides will provide more insight into their benefit. Potentially providing a high spatial resolution without sacrificing sensitivity. Allowing to perform accurate and localized analysis for material testing, including local stress concentrations and defects.

Acknowledgements

This work was supported as a Fraunhofer LIGHTHOUSE PROJECT (QMag). We acknowledge financial support from the Ministry of Economic Affairs, Labor and Housing of the State of Baden-Württemberg, Germany. Thanks also to Ralph Sperling from Fraunhofer IMM for manufacturing the flux guides.

References

[1] F. Giudice and A. Sili, “A theoretical approach to the residual stress assessment based on thermal field evaluation in laser beam welding,” Int J Adv Manuf Technol, vol. 123, 7-8, pp. 2793 (2022).

[2] D. C. Jiles, “Theory of the magnetomechanical effect,” J. Phys. D: Appl. Phys, no. 28, p. 1537 (1995).

[3] M. Roskosz and M. Bieniek, “Evaluation of residual stress in ferromagnetic steels based on residual magnetic field measurements,” NDT & E International, vol. 45, no. 1, pp. 55 (2012).

[4] M. W. Mitchell and S. Palacios Alvarez, “Colloquium: Quantum limits to the energy resolution of magnetic field sensors,” Rev. Mod. Phys., vol. 92, no. 2 (2020).

[5] P. Koss, A. R. Durmaz, A. Blug, G. Laskin, O. S. Pawar, K. Thiemann, et al., “Optically Pumped Magnetometer Measuring Fatigue-Induced Damage in Steel”, *Applied Sciences* 12 (3), pp. 1329 (2022).

[6] K. Thiemann, A. Blug, P. Koss, A. Durmaz, G. Laskin, A. Bertz, F. Kühnemann, T. Straub, “Using optically pumped magnetometers to identify initial damage in bulk material during fatigue testing,” *Proc. SPIE 12133, Quantum Technologies 2022*, 121330F (2022).

[7] Gen-2 Zero-Field Magnetometer (QZFM). QuSpin, Inc., 331 South 104th Street, Suite 130, Louisville, CO 80027, USA. QuSpin.com (20.01.2023)

[8] Y.J. Kim, I. Savukov, “Ultra-sensitive Magnetic Microscopy with an Optically Pumped Magnetometer,” *Scientific reports* 6, 24773 (2016).

[9] A. Blug, F. Abt, L. Nicolosi, A. Heider, R. Weber, D. Carl, et al. “The full penetration hole as a stochastic process: controlling penetration depth in keyhole laser-welding processes,” *Appl. Phys. B* 108 (1), pp. 97 (2012).