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Requirements for 3D Magnetostriction Measurement Instruments

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Abstract—This paper concerns the requirement analysis and implementation of a measurement instrument which can identify the 3D magnetostriction strain. To measure magnetostriction, a high-accuracy magnetic flux density and strain measurement are required, while the mechanical stress in the sample is minimized. The Full Block Tester (FBT) is proposed as a measurement instrument. In this instrument, homogeneity of flux density within the measured sample and the strain measurement resolution are sufficient, but stress caused by magnetic forces is higher than required.

Index Terms—magnetostriction, parameter extraction

I. INTRODUCTION

Magnetostriction is a parasitic phenomenon of interest to the high-precision industry, where ferromagnetic materials are used in constructions. Deformation resulting from magnetostriction reduces the position accuracy. The deformation is caused on a microscopic scale by magnetic field induced strain of single magnetic domains [1], redistribution of domains with unequal strains, and rotation of magnetization within domains [2]. Compensation of the deformation requires a three-dimensional description of magnetostriction.

Both magnetic forces and magnetostriction cause strains in ferromagnetic materials. In 2D magnetostriction measurement instruments for strips, the strains resulting from magnetic forces act in the direction perpendicular to the magnetostriction measurement directions [3]. No measurement method for 3D magnetostriction of blocks is given in literature [4] [5]. For 3D magnetostriction measurement instruments, a different method is required to differentiate between the strains caused by magnetic forces and magnetostriction.

The measurement of magnetostriction is challenging since only the combination of strain caused by magnetic forces and magnetostriction can be measured, and the strain caused by magnetic forces can be of the same order of magnitude as the magnetostriction strain. Additionally, the mechanical stress caused by the magnetic forces affects the magnetostriction.

In this paper, the measurement of 3D magnetostriction on a cuboidal sample of Invar using the Full Block Tester (FBT) is discussed. General requirements for measurement instruments which can measure the 3D magnetostriction are analyzed. Firstly, the mechanical design of a measurement instrument which allows to separately identify the strain tensor elements is given. Secondly, the magnetic design, which is required to obtain a homogeneous magnetic flux density and low magnetic forces, is shown. Finally, indications on how to improve the performance of the FBT, and design suggestions for 3D magnetostriction measurement instruments are given.

II. DESCRIPTION OF MAGNETOSTRICTION

Magnetostriction is a local strain induced in ferromagnetic materials as function of the local magnetic flux density B. This strain is also dependent on the local mechanical stress σ. Magnetostriction strain can be described as a strain tensor by

$$\varepsilon^{ms}(B, \sigma) = \begin{bmatrix} \varepsilon^{ms}_{xx}(B, \sigma) & \varepsilon^{ms}_{xy}(B, \sigma) & \varepsilon^{ms}_{xz}(B, \sigma) \\ \varepsilon^{ms}_{yx}(B, \sigma) & \varepsilon^{ms}_{yy}(B, \sigma) & \varepsilon^{ms}_{yz}(B, \sigma) \\ \varepsilon^{ms}_{zx}(B, \sigma) & \varepsilon^{ms}_{zy}(B, \sigma) & \varepsilon^{ms}_{zz}(B, \sigma) \end{bmatrix},$$

which is a symmetric matrix. Each element of the strain tensor describes a normal (diagonal elements) or shear (off-diagonal elements) strain. The goal of this research is to identify the elements of the magnetostriction strain tensor for a static magnetic field. To limit the scope of the initial measurements, the magnetostriction strain values are determined in the absence of mechanical stress. The range of interest of the magnetic flux density is 50 mT to 1.0 T.

III. MEASUREMENT INSTRUMENT AND REQUIREMENTS

To measure the magnetostriction, the Full Block Tester (FBT), shown in Fig. 1, was designed and built. The principle

![Fig. 1. Full Block Tester (FBT).](image)
which mirrors are attached. Strains are calculated from the measured displacements.

To compensate for the deformation in the photolithographic application with sufficient accuracy, an accuracy of 0.005 ppm is required for the elements of the magnetostriction strain tensor. No measurement data of the shape magnetostriction of Invar is available. Therefore, the required accuracy of flux density measurement and maximum coupling between measured strain elements is estimated at 10% of the measured value. The effect of mechanical stress on magnetostriction of Invar is unknown.

A. Mechanical design of the FBT

The mechanical design should provide measurement of all strain elements, while mechanical stress in the sample is minimized. Thin strip measurement instruments often apply strain gauges, which can only achieve a 0.1 ppm accuracy. Therefore, for the FBT, a laser interferometer system consisting of an Agilent 5517D HeNe laser source, Hewlett-Packard 10706A plane mirror interferometers, and Agilent E1708 remote dynamic receivers have been used. The length, height, and width of the cuboidal sample are 50 mm, such that a 0.25 nm accuracy of displacement measurement is required, while the resolution of the interferometer system is 0.15 nm. Changes in air pressure and temperature result in low frequency noise in the measured displacement. The displacement is averaged over 200 measurements to achieve the required accuracy.

Mechanical stress in the sample can result from applied forces on the sample, a net magnetic force on the sample, local magnetic forces, or magnetostriction itself. Externally applied forces on the sample are prevented by an air gap between the sample and the yoke. The sample is mounted such that strain in any direction is not restricted since restriction of magnetostriction strain leads to mechanical stresses.

The displacement of a point of a body is defined by the 12 independent parameters of translation, rotation and strain. The translation and rotation of the sample are minimized by restricting the rotation around all three axes and the displacement of a single point of the sample in all directions. Under these conditions, translation is only dependent on strain, and the six parameters of the strain tensor can be measured by six independent displacement measurements. Mirrors are attached to the sample, and their displacement is measured by the interferometer system.

The rotation of the sample around axis $q_t$ is constrained by the restriction of displacement in direction $a$ of two points of the sample, $r_1$ and $r_2$, with

$$q_t = (r_1 - r_2) \times a.$$  \hspace{1cm} (2)

Displacement of points $r_a$, $r_b$, and $r_c$ of the sample are restricted from moving in the directions indicated by the bold arrows in Fig. 2, in order to achieve restriction of rotation around all axes. Table I shows which combinations of restriction prevent rotation around which axis. The restrictions of displacement of the three points of the sample are implemented by connecting the sample to the table differently at each point, as illustrated in Fig. 3. The translation of point $r_a$ in the $x$-, $y$-, and $z$-directions is restricted by mounting the point rigidly to the stationary table. The translation of point $r_b$ in the $z$-direction is restricted by a sliding contact which allows displacement in the $x$- and $y$-directions. The translation of point $r_c$ in the $x$- and $z$-directions is restricted by attaching a flexure between the sample and the table which only allows displacement in the $y$-direction [6]. The bottom of the sample is not supported by the table, since there is a hole in the table slightly wider than the sample. With the described restrictions, only the expansion in the $y$-direction is restricted to some extent by the stiffness of the flexure.

If the strain in the sample is homogeneous, the rotation of the sample around all axis is restricted, and the point $r_a$ has zero displacement and is located in the origin of the coordinate system, the displacement $u$ of a point $r$ in the sample is given by

$$
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{xy} \\
\varepsilon_{xz}
\end{bmatrix}
= 
\begin{bmatrix}
\varepsilon_{xx} & 0 & 2\varepsilon_{xy} \\
2\varepsilon_{xy} & \varepsilon_{yy} & 2\varepsilon_{yz} \\
0 & 0 & \varepsilon_{zz}
\end{bmatrix}
\begin{bmatrix}
u_x \\
u_y \\
u_z
\end{bmatrix}
= 
\begin{bmatrix}
u_x \\
u_y \\
u_z
\end{bmatrix}.
$$  \hspace{1cm} (3)

Hence, the strain matrix can then be derived from the displacement of points $r_b$, $r_c$, and $r_d$. The double value of the shear strain elements results from the applied restrictions. Displacement in the $z$-direction cannot be measured, since the yoke obstructs the measurement in this direction. The strain in the direction of the applied field can be derived from the measurement of other strain elements, if the volume magnetostriction is assumed negligible.

The displacements of three points are measured simultaneously by the interferometer system. The sample can be rotated in 90 degree steps around the $z$-axis to obtain all required displacement measurements without altering the interferometer system. By re-mounting the sample on the table, after rotating it by 90 degrees around the $x$- or $y$-axis, strain in the $z$-direction as function of flux density in the $x$- or $y$-direction can be measured.

The elements of the strain matrix can be determined sepa-
rately if the displacements of the sample in the FBT satisfy (3). Three sets of mechanical FEM simulations of the deformation of the sample have been performed to determine the coupling between the measured elements of the strain tensor. In these simulations, all components of the strain tensor were set to zero, except one of the normal strains, which was set to $10^{-6}$ in the volume of the sample. Figure 4 shows the result of the simulations in which $\varepsilon_{xx} = 10^{-6}$ (top), $\varepsilon_{yy} = 10^{-6}$ (middle), and $\varepsilon_{zz} = 10^{-6}$ (bottom).

With only strain in the $x$-direction, the simulated deformation is equal to the deformation in the idealized situation. This is mainly because no friction between sliding contact at $r_b$ and the table is assumed in the simulation. With only strain in the $y$-direction, the flexure restricts expansion, such that a 24% error occurs for the simulated displacement in the $y$-direction. In this case there is also a maximum coupling of 12% to the simulated shear in the $xy$-plane and a coupling of 13% to shear in the $xz$-plane.

In the $z$-direction, the coupling to the simulated shear strains in the $xz$- and $yz$-planes are not within the requirement. Restriction of expansion of the sample at the facets that are connected to the mounting result in tilting of the sample. The simulations show that for four of the strain elements, the decoupling is not within the required 10%. Therefore, there will be a cross-coupling between the measured strain elements, and the error of the measured values of the strain elements cannot be guaranteed to be smaller than 10%.

### B. Magnetic design of the FBT

The magnetic design of the measurement instrument should provide a homogeneous flux density in the sample while deformation of the sample resulting from magnetic forces is minimized. The yoke and sample are the only ferromagnetic parts of the FBT.

With a homogeneous magnetic flux density in the sample, the measured strain can be related directly to a value of flux density. A flux density with a standard deviation between 3.0% and 6.2% over the range of interest is achieved by placing a C-shaped magnetic yoke around the sample, with the sample placed symmetrically in the air gap. The dimensions of the yoke are optimized for maximum homogeneity using 3D FEM simulations, the dominant parameter being the area of the faces of the air gap. Figure 5 shows the flux density in the $xz$-plane through the center of the sample and yoke, where the homogeneity is lowest, for an average flux density of 0.26 T. In the FBT, the flux density in the sample is monitored during measurement by a secondary coil as a flux sensing coil. The sample can be demagnetized in-place after inserting ferromagnetic sheets in the air gap.

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Fig. 3. Top view of the mounting of the sample. The sample is connected to the table at three points only.

Fig. 4. Simulations showing deformation, meshed: original shape, solid: displacement magnified by a factor $10^5$. The strain tensor is set to zero, except $\varepsilon_{xx} = 10^{-6}$ (top), $\varepsilon_{yy} = 10^{-6}$ (middle), and $\varepsilon_{zz} = 10^{-6}$ (bottom).

Fig. 5. Simulated magnetic flux density in the cross section through the center of the sample (center left) and C-shaped yoke, showing homogeneity of magnetic flux density in the sample.
The measured displacement of the point given in Table II. From this table it is clear that the required positioning accuracy of the yoke relative to the sample, at a flux density of 250 mT in the sample, is determined by magnetic forces on the sample as function of relative positioning accuracy, was determined using FEA. The stiffness of the used magnetized fluid resulted in much smaller than displacements caused by magnetostriction. Therefore, an alternative strain measurement method is required, which is not sensitive to rotation or translation of the sample. This can be done by adding measurement axes to determine translation and rotation, or by mechanically coupling the measurement device and sample such that they have no relative rotation and translation. The coupling between measured strain elements is higher than the required 10%. This could be solved by decreasing the contact area between mounting and sample, and improving the properties of the flexure.

Strain caused by magnetic forces should be either prevented by changes in the magnetic design, or by adding a facility to oppose the magnetic forces acting on the sample. An instrument in which the magnetic forces on the sample are sufficiently low can be designed if the magnetic force density is insufficient for decreasing the magnetic forces to levels much smaller than displacements caused by magnetic forces. This could be solved by decreasing the contact area between mounting and sample, and improving the properties of the flexure.

Strain caused by magnetic forces can be determined by the virtual work method [8], for which an energy function of the material is required.

### REFERENCES


