A pulse field magnetometer for local magnetization measurements

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Abstract

A pulse field magnetometer with a new flat pick-up coil device is presented for the characterization of magnetic materials in high magnetic fields. The dimensions of this pick-up coil allow the registration of local hysteresis loops. Magnetization measurements and anisotropy field measurements were performed locally on Nd-Fe-B and M-type ferrite permanent magnets at room temperature. Estimation of the local demagnetizing factor by the measurement of $H_A$ using the SPD technique is presented. Local hysteresis loops show the eddy current effect in conducting magnetic metallic samples. The field calibration with the surface coil is also discussed.

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1. Introduction

The study of magnetic materials in high magnetic fields can deliver valuable information, such as high field susceptibility, saturation magnetization as well as anisotropy field. Till now, the most measurements are done using pick-up coil systems, which are wound around the sample (WSC). This work aims towards testing a system which allows the measurement of the local magnetization with a high degree of coupling. For this purpose an arrangement of small flat pick-up coils (SFC) was tested. The axial dimensions of the SFC are less than 1 mm, diameter about 3 mm and are attached close to the surface of the sample. Due to their small size, local magnetization measurement can be performed.

Measurements of the local hysteresis loops and local anisotropy field ($H_A$) using the SPD technique [1] provides a new method for the investigation of magnetic materials. Local measurements can give inside information concerning the effect and distribution of eddy current in conducting magnetic metallic samples. Investigations of the homogeneity of large magnet samples can be done by the local hysteresis loops measurements. The effect of the local demagnetizing field can also be studied. We report here, a unique local measurements in the large magnetic samples using high pulsed field.

2. Experimental setting

A pulsed field magnetometer consists of a condenser battery, a charging unit, a high field magnet, a rod—where the pick-up coils system can be mounted so that the sample is fixed, the measuring electronics—composed of amplifiers, and the filters (integrator, differentiator). A detail description of a pulsed field magnetometer can be found elsewhere [2,3]. The measuring electronic is linked to a transient recorder (Krenz electronic, model 6070), which is controlled by a personal computer. The magnet was specially designed to perform measurements in large magnetic samples, containing a large axial $N/N$ pick-up coil system (LPC) with a bore of 50 mm, details are given in [4]. Measurements were performed at room temperature to compare the results obtained using the SFC system with the volumetric LPC system.

The surface coils were produced by Magnet-Physik; Dr. Steingroever GmbH and the effective winding-area was supplied by the producer. The sample holder is composed of an arrangement of three compensated SFC systems. Three sensing SFC were placed along the radius of the holder, labeled according to its radial position (inner (I), middle (M), and outer (O)), and separated by 7.5 mm from each other. The compensation is achieved with a second SFC, which is placed in the same radial position, but in this case 15 mm from the surface coils in the axial distance. This coil is connected in series (opposite winding sense) to the magnetization-sensing SFC. The sample holder has an additional SFC ($S_H$) to measure the applied field by the induced...
signal. The sample to be measured should have flat surfaces (cylinders, disks, and cubes) to guarantee the best sample-coil coupling.

3. Calibration

3.1. Calibration of the field

The field calibration for hysteresis and anisotropy field measurement can be performed either by the metamagnetic transition of a MnF$_2$ single crystal; this calibration works only at 4.2 K [5], or another possibility, is to use the anisotropy field ($H_A$) of a well known and characterized sample like BaFe$_{12}$O$_{19}$, which is well suited for calibration at room temperature [6,7]. The anisotropy field is then measured applying the SPD technique [1]. In our case, the field calibration was performed using the law of induction. Combining the solution of the equation of the RLC circuit and the faraday law of electromagnetic induction one get:

$$V_{\text{ind}}(t) = A_{\text{eff}} D_0 \omega e^{-\beta t} [\beta \sin(\omega t) + \omega \cos(\omega t)] \quad (1)$$

Eq. (1) describes the voltage induced by a coil due to the presence of a damped oscillating applied field. The parameters $\beta$ (damping factor), $\omega$ (frequency in rad/s), and $D_0$ (V/m$^2$) were obtained by fitting the induced voltage $V_{\text{ind}}(t)$ using (1). The effective winding-area of $S_4$ is $A_{\text{eff}} = 5.505 \times 10^{-4}$ m$^2$. A calibration constant of 1.779 T/V s was obtained for the field coil attached in the sample holder. The calibration procedure using just the law of induction is very favorable because it is independent of the temperature, it scales linear with the field, and it is an absolute method for determining the calibration factor. Its accuracy is mainly determined by the knowledge of the effective winding-area, which can be obtained by NMR. Performing all steps carefully, an absolute accuracy of 1% is possible.

3.2. Calibration of magnetization

The calibration of magnetization using WSC coils is very straightforward. The induced signal of the WSC is proportional to the volume of the sample. To investigate the mass proportionality, when the SFC coil is used, a set of 10 cylinder of the same material (Sr-Fe-O, HF24/23

![Hysteresis loops](image_url)

Fig. 1. Hysteresis loops from the HF8/22 sample with a diameter of 30 mm. Each loop is labeled according to the position of the flat pick-up coil with respect to the radius of the sample.
supplied by MS MagnetFabrik Schramberg) with diameter $d = 10\, \text{mm}$ and height from 1 to 10 mm were used at room temperature.

The obtained signal increases non-linear with the height, which means also with the mass. Information concerning only the surface of the sample is, in all cases, superseded by the signal that results from the bulk. Calibration of the magnetization using the same geometry for the calibration sample and the sample under test, seems possible in order to obtain magnetization measurements in physical unit. Studies to give better conclusions about the calibration of the magnetization are still in progress.

4. Local measurements

Measurements of the local hysteresis loops and the local magneto-crystalline anisotropy field $H_A$, were done with the sample holder SH1 on a commercial isotropic Barium M-ferrite sample (Schramberg: HF8/22) with cylindrical shape ($d = 30\, \text{mm}$ and $h = 5\, \text{mm}$) and a sintered Nd-Fe-B magnet ($d = 30\, \text{mm}$ and $h = 3\, \text{mm}$). Both samples were measured with the LPC system in order to compare each other.

Fig. 1 shows the hysteresis loops measured at room temperature, on the surface of the sample HF8/22 obtained with the system SH1 where local different SFC systems (I, M, O) are available. The loops are labeled corresponding to the position of the flat pick-up coil. It is evident that the inner and the middle loop are quite similar. They are sheared with the same degree of inclination, and the saturation value is also similar. The outer loop has a higher value of saturation, which results from the stray field close to the boundary (edges) of the sample. The slope there is smaller than that of the preceding ones. All of the three loops have the same coercive field $H_C$, which can be expected because at the coercivity the demagnetizing field is zero. Additionally, there are no eddy currents in a non-conducting material. Measuring the anisotropy field $H_A$ at each position is a new method to estimate the value of the local demagnetizing factor. The value of $H_A,\text{ext}$ is obtained using the SPD technique where the peaks of the $dM/d^2$ versus $H_A,\text{ext}$ occurs at $H_{\text{ext}} = H_A,\text{ext}[1].$
The local magnetometric demagnetizing factor $N_{ml}$ was calculated by:

$$N_{ml} = \frac{H_{A,ml} - H_{A,im}}{J_s} \quad (2)$$

where $H_{A,im} = 1.65 T$ is the internal anisotropy field of BaFe$_2$O$_4$ at room temperature and $J_s = 0.41 T$ the saturation polarization. The demagnetizing field inside the cylindrical sample is not homogeneous. Close to the radius of the sample its influence is small, whereas the demagnetizing fields for the inner and the middle position are similar. From theoretical calculation, it is well known that magnetization and demagnetizing field is only homogeneous in ellipsoidal bodies. Table 1 gives the local $N_{ml}$ values calculated using (2) and the volumetric magnetometric demagnetizing factor given by Chen et al. [8].

A comparison of the values from Table 1 show that the local demagnetizing factor obtained at the center of the sample (inner) is similar to the value for the volumetric case reported in the literature. The value of $N_{ml}$ for the middle position is quite similar to the value at the center of the sample (inner). The similarity is related to the fact that the stray field is quasi-homogeneous in the region (RM) where the inner (I) and the middle (M) flat pick-up coils are located respect to the radius of the sample. The demagnetizing factors obtained on the RM region demonstrate that the theoretical values of $N_{ml}$ reported in the literature for non-ellipsoidal bodies are approximations, and they are valid only at the center of the sample [9].

Table 1: Local demagnetizing factors measured along the radius of the HF8/22 sample.

<table>
<thead>
<tr>
<th>Theory</th>
<th>Inner</th>
<th>Middle</th>
<th>Outer</th>
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<tbody>
<tr>
<td>0.7385</td>
<td>0.739</td>
<td>0.729</td>
<td>0.34</td>
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5. Conclusions

The measurement system presented in this paper opens a new method for investigating the magnetic materials in high magnetic fields. The distribution of the demagnetizing field inside the sample and the influence of the stray field according to the radius of the sample can be studied. Eddy currents can be studied as well, and a mapping of the surface of a large conducting magnet is possible. The intention of using such flat pick-up coil is not to substitute the standard pick-up coil systems, but to complement and give more options in the analyses and study of magnetic materials. It was shown the suitability of using the flat pick-up coil for field calibration. Due to its small size and known effective area, such device can be used for field calibration in standard high field facilities.

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