THREE-CHANNEL NON-FORCE MAGNETIC MICROSCOPE

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ABSTRACT. The development of a scanning magnetic microscope (MM) without appreciable applied forces or magnetic excitations on specimens is presented. The magnetic microscope is intended to measure weak magnetic field distributions near the object surface at micron and sub-micron scales. Specifically, the MM consists of three measurement units with respective output channels. The first channel uses a special fluxgate magnetometer as a field detector, and is designed for magnetic study of a specimen surface at room temperature (T=300K), with a magnetic sensitivity of $10^{-9}$ T, at a spatial resolution of 10μm in a scan area of 10x10 mm. The second channel uses a HTSC SQUID and a ferromagnetic flux concentrator, and is intended for detailed study of a room-temperature object at the sensitivity of $10^{-12}$ T with 0.1-1 μm resolutions. The third component also uses the SQUID-concentrator combination, but is intended for detailed study of the object at liquid-nitrogen temperature (T=77 K), covering the area of 100x100μm.

INTRODUCTION

Four types of magnetic microscopes (MM) are well known to date:
- magnetic force microscope (MFM);
- magnetic SQUID microscope (MSM);
- magnetic Hall microscope (MHM)
- magnetic eddy current microscope (MECM).

Each of the MM classes distinguishes itself by the type of magnetic detector that scans over a testing object (TO) surface.

There is an extremely small needle in design of MFM [1] manufactured from magnetic hard material. The attractive force of a needle to TO can be measured and the measurement gives the information about the value of the TO magnetic moment (M) at a given location of the probe. The attractive force depends on M and the distance (t) between the TO and needle. It is therefore necessary to choose t values to be tens and hundreds of angstroms in order to achieve the spatial MFM resolution of tens of angstroms. In some cases the said force interaction results in irreversible changes of TO properties. In reality, the scanning range by MFM often becomes the order of microns for actual research time scales.

The MSM detector [2] is either a SQUID interferometer or an extremely small (of some micron diameter) coil of a flux transformer coupled with a SQUID. This detector, in comparison with MFM detectors, has no force or magnetic effect on TO. While it is advantageous as being a really passive detector, it has a disadvantage in terms of spatial resolution. The detector size and the need for thermal insulation prevent the detector from approaching the object in angstrom distances. Thus, MSM cannot achieve high spatial resolution.
resolutions characteristic to MFM, especially in "warm" (T=300K) TO cases. Indeed, the MSM spatial resolution is typically not better than some microns. The rather large distance between the MSM detector and the TO is partially compensated by high SQUID magnetic sensitivity. However, there is a significant trade-off between very high SQUID magnetic-flux sensitivities and desirable minimum sizes of the detector. Consequently, MSM detectors have, as a rule, sensitivities to a local TO field of not better than 10^{-9} to 10^{-10} T. Because of the significant overall dimensions and weight of the SQUID cryogenic equipment, the TO should be moved instead of detector. Also as a rule, MSM allows to measure vertical component of a magnetic flux created by TO.

The MHM probe is an extremely small semi-conducting structure of a triangular shape, its acute angle being pointed toward the TO. This probe is essentially passive, has lower magnetic sensitivities than that of MSM, and can approach the TO surface with some micron lift off with the corresponding spatial resolution of TO. MECM uses an inductive coil with a ferrite core having a narrow slot, and measures horizontal components of alternating magnetic fields produced by induced eddy current within TO. It does not work for DC field measurements.

The present article describes a principle of operation and design of a new three channel MM, consisting of two improved HTc SQUID measuring channels and of a uncooled channel based on a special fluxgate magnetometer. This MM allows to study both "warm" and "cold" objects, at temperatures down to liquid nitrogen (77K). Principal distinctive features of the new MM are:

- application of the ferromagnetic concentrator of a magnetic flux between SQUID and TO [3] and also in a fluxgate magnetometer;
- usage of a special fluxgate sensor having sufficiently high sensitivity to a magnetic field of dipole sources with high spatial resolution.

The MM uses ferromagnetic needles as the field concentrator that bridges fields between a TO surface point and the SQUID aperture. Since it allows the use of highly sensitive SQUIDs of a finite size, the MM achieves both high resolution and high sensitivities simultaneously. The new MM allows measurement of a vertical component of a TO magnetic flux. In what follows, we summarize the advantages of our MM:

- better magnetic sensitivity than traditional MSM and MHM;
- better spatial resolution than traditional MSM;
- possibility, in principal, to measure all three components of the object magnetic field simultaneously, unlike MFM;
- absence of appreciable force influence on the object unlike MFM;
- possibility to measure alternating and direct magnetic field unlike MECM.

THE DESCRIPTION OF A THREE CHANNEL MM DESIGN

The schematic of the MM channels and the basis units is given in Fig. 1. The external view of MM is shown in Fig. 2. The channels located in the middle and on the right are used for a TO study at T=300K, while the channel on the left side is used for a TO testing at T=77K. The first two channels contain the two-axis motion-controlled scanning tables. The specimen holder is mounted on the scanner table as shown, and placed under either a central fluxgate channel or a right SQUID channel.
FIGURE 1. Design Schematic of Magnetic Microscope, including EC-Electronic Converter; PA- Preamplifier; ADC 16-Analog Digital Converter 16-bit Resolution; DDSM-Drive Device Stepper Motors; SM-Stepper Motor.
FIGURE 2. External view of magnetic microscope: 1-measuring channel with SQUID for study of the "cold" objects, 2-measuring channels with fluxgate for study of the "warm" objects, 3- measuring channel with SQUID for study of the "warm" objects, 4- scanner driving device, 5- SQUID and fluxgate electronic amplifiers, 6- personal computer.
During a TO study at $T=300K$, a fluxgate channel may be used first, that allows preliminary examination of a 10x10 mm area with spatial resolution up to 10 microns and with sensitivity up to $10^9$ Tesla. After finding a region of the most interest, the TO may be moved under the right SQUID channel, which performs imaging of a 100x100 micron square area at the 0.1 to 1 micron resolution and at the sensitivity up to $10^{12}$ Tesla. The HTc SQUID is manufactured from a high temperature superconductor YBa$_2$Cu$_2$O$_{7-\delta}$ and has an operation temperature close to 77K.

The left-hand channel has also HTc SQUID with the ferromagnetic concentrator. The detector characteristics in terms of sensitivity and spatial resolution are identical between the left and right SQUID channels. In the left channel, however, the TO holder is inserted into the nitrogen cryostat from above. The 2D-scanner is mounted on top of the cryostat. For magnetic shielding, the channels are supplied with three layers of permalloy shields which suppresses low frequency magnetic fields by more than 100 times and high frequency by more than 1000 times.

The high spatial resolution of the designed MM is the result of the combination between the magnetic field detector and the ferromagnetic needle as a magnetic concentrator. The SQUID detector and concentrator locations relative to the TO is shown in Fig.3. Figure 4 shows the dependencies of the magnetic flux through the detector (for example, contour of an interferometer) on the distance to the TO in the two cases, i.e. with and without the concentrator.

To meet the high channel parameter requirements of the fluxgate channel, the special design of the fluxgate sensor was applied (see Fig.5). The fluxgate sensor resembles a closed ferromagnetic circuit (1) with two pointed ends, their radius of curvature being not more than 10 microns. One of these ends is the detector tip of the fluxgate. It is pointed toward the TO surface with a lift off up to 10 microns. The drive coil (2) magnetizes the detector yolk with AC frequency $f$, while the pickup coil (3) registers the output voltage at the frequency $2f$. The triangle part connecting the sensor tip and the pickup coil serves as a magnetic flux concentrator.

Several preliminary testing of the fluxgate channel have been carried out to date. We have scanned over:
- a meandering coil made of a copper microwire driven by a current (Fig.6);
- a magnetic tape piece with linear stripes recorded, with the stripe density of 3 stripes per mm (Fig.7);
- a ferromagnetic particle of approximately 400 $\mu$m in diameter (Fig.8).
Measurement results correspond to predicted values, thus proving efficacy of the MM channel design.

**POTENTIAL NDE APPLICATIONS OF MAGNETIC MICROSCOPE**

The low-field sensitivity of the MM is suitable for NDE of multi-layer metal structure, hidden corrosion and cracking detection. For these applications, the fluxgate sensor has superior sensitivity over Hall and GMR sensors. High-Tc SQUID has even higher sensitivity than fluxgate sensors, while it can be built into a portable instrument.

The high resolution of MM can be taken advantage of to enable image-based electromagnetic NDE for surface-crack imaging and composite material (metal-matrix, carbon-carbon) inspections.
FIGURE 3. The schematic of the high-Tc SQUID detector with flux concentrator (2) for a measurement of the surface magnetic field of the sample (1), 3-external wall of the nitrogen cryostat, 4-vacuum, 5-interferometer weak link, 6-HF interferometer, 7-heat exchanger, 8-inner wall of the nitrogen cryostat, 9-liquid nitrogen, 8-small vacuum slot.

FIGURE 4. Dependencies of the magnetic flux ($\Phi$) through the interferometer on its distance ($z$) to a magnetic point source in the sample without the concentrator (1) and with the concentrator (2).

FIGURE 5. The schematic of the fluxgate detector: 1- ferromagnetic circuit; 2-excitation coil; 3-coil for generating the output voltage ($V_{ex}$); 4-testing object.
FIGURE 6. A MM image of the vertical component of a magnetic field over two micro wires with an opposite direct current $I$, wire diameter of 70 $\mu$m, and distance of 80 $\mu$m between the wires.

FIGURE 7. A MM image of the vertical component of a magnetic field over a tape (band) with the linear magnetizations (3 Y-lines/mm along the X axis).
FIGURE 8. A MM image of the vertical component of a magnetic field over a small magnetic particle of approximately 400 μm in diameter.

The combined capabilities of the low-field sensitivity, high resolution, and no force properties of MM enable new classes of NDE applications. The potentials include biomedical magnetic-field detection (functional imaging via blood-flow detection, brain-wave mapping), and NDE of fluid specimen containing magnetic particles.

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REFERENCES