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Title: DESIGN AND PRELIMINARY RESULTS FROM A HIGH TEMPERATURE SUPERCONDUCTING SQUID MILLISCOPE USED FOR NON-DESTRUCTIVE EVALUATION

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Design and Preliminary Results From a High Temperature Superconducting SQUID Milliscope Used for Non-Destructive Evaluation

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Abstract— **We present the design and preliminary results from a SQUID 'milliscope'. The device was designed for non-destructive evaluation (NDE) as part of the Enhanced Surveillance Program at Los Alamos National Laboratory and uses a high temperature superconducting (HTS) SQUID sensor to map magnetic fields induced in the sample. Eddy currents are induced in the conducting sample by a wire coil designed to produce minimal magnetic field at the SQUID when no sample is present. The features of interest are characterized by anomalies in the induced magnetic field. The goal of the instrument is sensitivity to small features generally buried under several intervening layers (~1-10 mm) of conducting and/or non-conducting materials and robustness of design (i.e. the ability to operate in a noisy, unshielded environment). The device has primarily focussed on specific NDE problems such as the ability to detect buried "seams" in conducting materials and quantify the width of these seams. We present the design of the instrument, and some data to demonstrate its capabilities.**

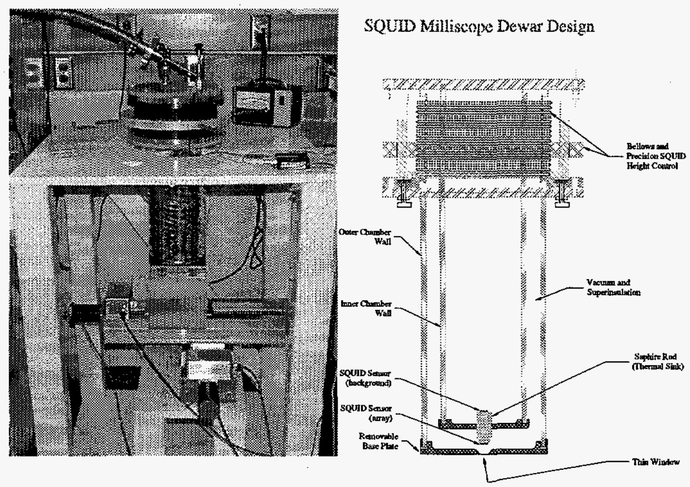

Fig. 1 (a). Photograph of dewar operating in our laboratory. Stepper motors (visible under the dewar) move a two-axis scanning stage that holds the sample of interest. (b) Schematic drawing of milliscope dewar. SQUID is located on the tip of a sapphire cold finger. Eddy current induction coils are located on the outside of the dewar just under the thin window.

I. Introduction

A. *Overview of the Problem*

The SQUID milliscope was designed to be a non-destructive evaluation (NDE) tool for stockpile stewardship as part of the Enhanced Surveillance Program (ESP) at Los Alamos National Laboratory. It is hoped that such devices will eventually be located at various inspection sites, where they will operate as one in a complimentary set of diagnostic tools.

The device is capable of sub-millimeter SQUID-sample distances, but is different in philosophy from a SQUID microscope of the sort described by refs. [1] and [2]. These devices attain high spatial resolution by getting the SQUID as close as possible to the sample. The features that we were asked to study were located under many intervening layers of conducting and/or non-conducting materials, far away from the surface of the sample, so getting the SQUID as close as possible is not necessarily beneficial. Also, the scale of the features of interest have thus far been ~mm and do not warrant a push to micron resolution. In these respects the device is more similar to the sort of NDE instrument described in ref. [3].

The goal is to be able to identify defects before having to take the component apart. Often, the instrument would be needed to observe and monitor the status of a known feature such as the width of a seam over time. These considerations shifted our focus from minimizing SQUID-sample distance to concentrating on assessing buried features. The device was designed with the practical aim of satisfying a customer with specific problems. The instrument has been operational since September 1997.

B. *Why a SQUID?*

SQUIDs are well suited to the problem of buried features. A conventional technique such as complex impedance measurement has to go to lower drive frequencies, ω, to get the required skin depth, δ, which results in a corresponding decrease in signal strength

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0}} \text{ and } V \propto \omega, \tag{1}$$

where ρ is the resisitivity of the material. Ultrasound has difficulties with the signal being reflected at intervening layers that are sonic absorbers (as are most plastics and electrical insulators). If the feature is below such a layer ultrasound may not be able to see it.

SQUID sensitivity is linear with frequency from Hz to kHz so there is no difficulty going to low frequencies for larger skin depth and the induction signal does not have difficulty with intermediate layers.

Techniques such radiography are also used but can be expensive and facility dependent. A SQUID system can be portable and comparatively inexpensive.

II. Instrument Design

Fig. 1a is a photograph of the SQUID milliscope in our laboratory. The device sits in a wooden stand and a two-axis scanning stage, located below the dewar, uses stepper

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motors to move the samples of interest. Fig. 1b shows a schematic drawing of the SQUID milliscope. The inner chamber is filled with liquid nitrogen. The SQUID, located in vacuum space, sits on the tip of a sapphire cold-finger which is in contact with the liquid nitrogen reservoir. At the bottom of the dewar is a thin (0.25 mm) quartz window of 1 cm diameter. During operation the SQUID is located ~0.13 mm back from the thin window. The distance between the SQUID and the top of the sample is typically 1 mm, although the feature of interest may be buried several millimeters in the sample.

The High Temperature Superconducting (HTS) SQUID is kept at ~78 K while maintaining its proximity to the outside world (due to the elevation of Los Alamos the temperature of liquid nitrogen is ~75 K). The SQUID is a Conductus "Mr. SQUID"™ chip with no pick-up coil (SQUID area 30 μm × 30 μm) and 700nT/Φ_0, controlled by Conductus pcSQUID™ electronics. Because of the small area of the SQUID, the instrument is able to operate unshielded in a very magnetically noise environment in our laboratory.

A. *Induction Coil Design*

The induction coils are designed to produce a "null" in the magnetic field at the location of the SQUID, thus the induction signal itself does not use all the dynamic range of the instrument. Two designs have been tried thus far, the first was two pairs of "double-D" coils rotated by 90° and the second was circle-within-rectangle design. Both are shown in the left panel of Fig 2 (only one pair of double-D coils is shown for simplicity).

Because of the large size of the double-D coils relative to the samples, eddy-currents at the edges of the sample produced large anomalous signals. With the circle-within-rectangle coil, most of these edge effects are avoided.

Two adjustable current generators with up to 150 mA of output current, driven by a common function generator, provide current to the two induction coils. Prior to data taking, the sample is centered underneath the milliscope,

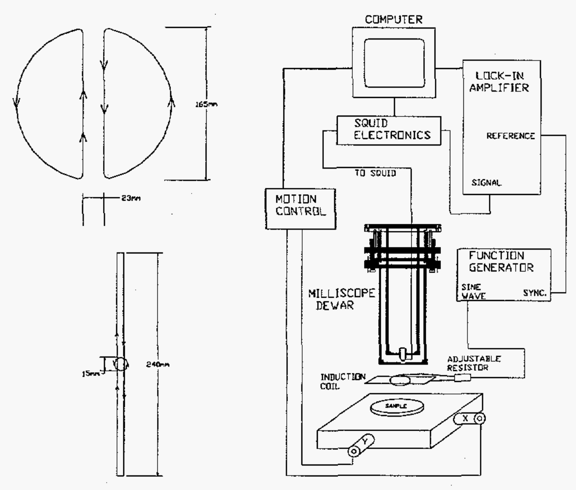

Fig 2. Left: Double-D induction and circle-within-rectangle induction coils. The arrows show the direction of current flow. SQUIDs are located at the center, where magnetic field due to the coils is zero. Right: Schematic diagram of milliscope and data acquisition system

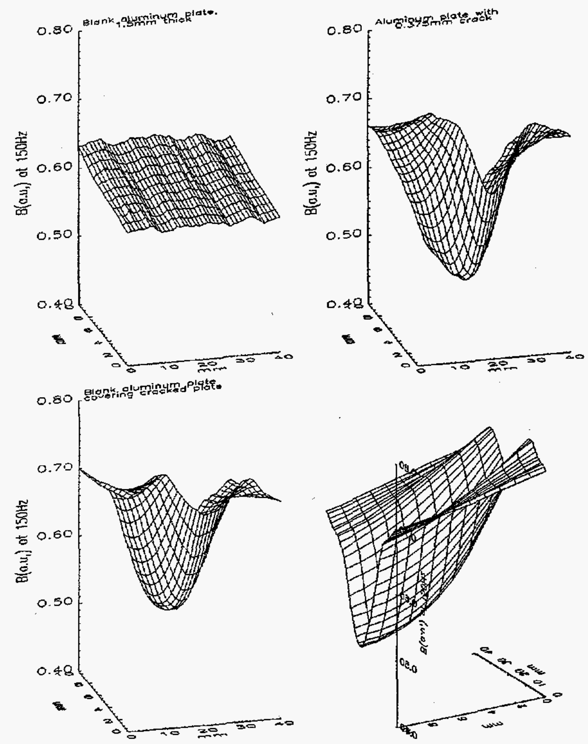

Fig. 3. Scan of blank Al plate (upper left), cracked Al plate (upper right), and cracked Al plate covered by an unflawed plate (lower left and right). Induction frequency was 150 Hz.

and the current in the coils is adjusted until there is a minimum magnetic field measured by the SQUID.

B. *Data Acquisition*

Fig. 2 (right) shows a schematic diagram of the milliscope and data acquisition system. A personal computer controls the SQUID electronics and the motion control system for scanning the samples. At each point the computer reads out the lock-in amplifier recording the SQUID's response amplitude and phase relative to the induction signal. A function generator provides the induction signal and the reference signal to the lock-in amplifier.

III. Initial Results

A. *Aluminum*

The milliscope began taking data in September 1997. Initial data used 150 mm × 150 mm, 1.5 mm thick aluminum plates. Flaws (cracks and holes) were put in some plates, while others were left blank. We experimented with looking at the flawed plates buried under the unflawed plates. Fig. 3 shows raw data (amplitude vs. position) for a blank aluminum plate (upper left), a plate with a crack (upper right) and a plate with a crack covered by an unflawed plate (lower left). A rotated view of the covered-cracked plate is also presented (lower right). The crack went all the way through the 1.5 mm plate material.

Raw data for an aluminum plate with holes of various diameters are presented in the upper panel of Fig. 4. The spikes in the data occur where the SQUID electronics unlocked, which was probably caused by magnetic

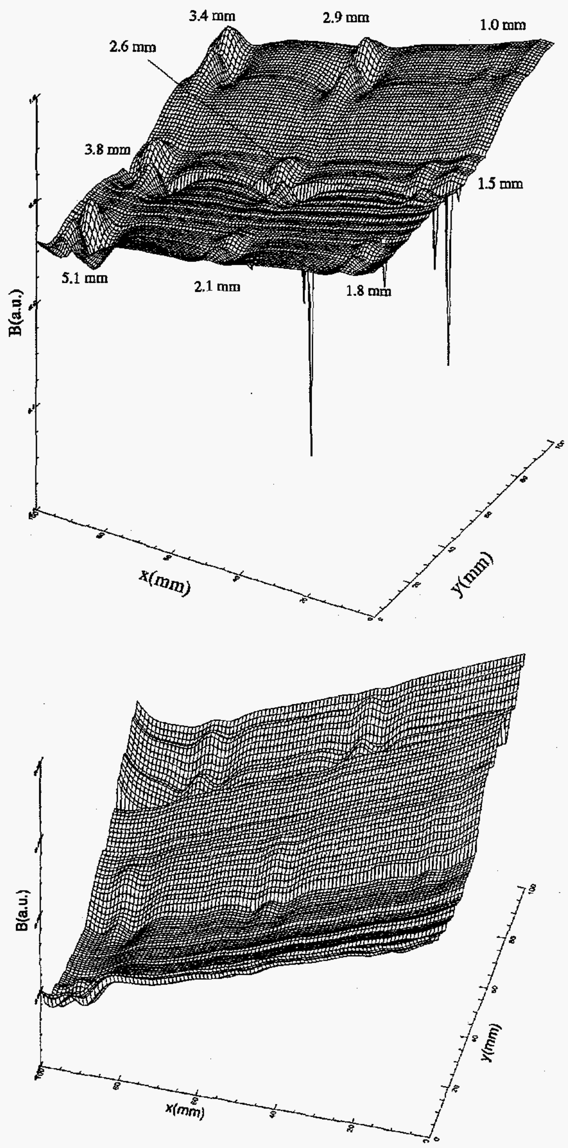

Fig. 4. Upper: Raw data for Al plate with holes of various diameters. The induction frequency was ~300 Hz. Lower: Data as in upper panel, with a 1.5 mm thick blank Al plate covering the plate with holes.

materials left around the edges of the holes when they were drilled. The lower panel of Fig. 4 presents data for the same plate covered by a blank.

B. Titanium Tungsten

A potential customer for the milliscope provided us with a surrogate made of titanium-tungsten, which had incurred a stress fracture. A picture is shown in the left panel of Fig. 5. The results of a single pass scan lengthwise over the surrogate are shown in the right panel of Fig. 5. It is worth noting that this surrogate was slightly ferromagnetic. The stress fracture was clearly observed, demonstrating sensitivity to lattice defects that do not necessarily evidence a physical separation. One edge of the surrogate is chamfered, and this feature is visible in the scan at 633 Hz.

C. Copper

The left panel of Fig. 6 shows a photograph of a 150 mm × 150 mm fiberglass plate coated with 100 μm of

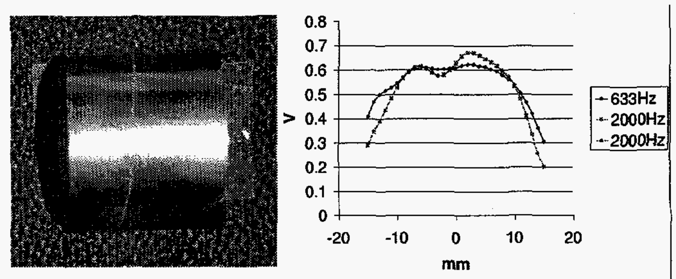

Fig. 5. Left: Photograph of titanium-tungsten surrogate with stress fracture. Right: Data from a single scan lengthwise down the surrogate.

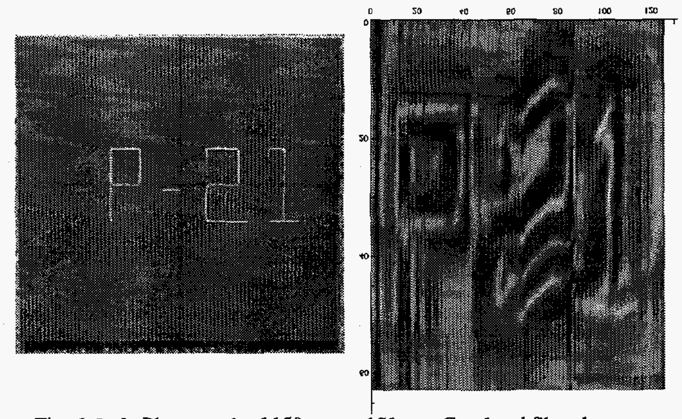

Fig. 6. Left: Photograph of 150 mm × 150 mm Cu-plated fiberglass plate with "P-21" scratched into the 100 μm thick Cu layer. Right: Raw data from a scan of the same plate.

copper. Using a razor blade, "P-21" (the initials of the Biophysics Group at LANL) was scratched through the copper layer, exposing the fiberglass beneath. The right panel of Fig. 6 shows the raw data for scan of the copper plate (induction frequency ~600 Hz). The letters are clearly visible. The "2" appears rotated because the plate was inadvertently moved for that portion of the scan.

To better understand the resolution of the instrument we placed closely spaced pairs of scratches on copper-plated fiberglass plates like the ones described above. Resolution was then defined as the ability to resolve the two scratches. The scratches were ~100 μm wide and 75 mm long and went through the copper. The scratch-pairs were separated by different distances. The SQUID-sample distance was ~1 mm. Results are shown in Fig. 7. The scratches 5 mm apart are resolved. Both the scratch-pairs of 3 mm and 1 mm separation appear as one scratch, although the 3 mm scratch-pair is wider. This exercise provides a benchmark that will be useful when we move on to different induction coil designs and eventually a SQUID array (discussed in section IV).

D. Titanium

A real problem for stockpile stewardship is monitoring the status of known seams over time. It is important to know whether or not the seams are changing width with age. These seams are typically buried ~1 cm beneath a conducting material. To test the milliscope's applicability to this problem we designed a simple sample made of 150 mm × 150 mm titanium plates that were 1 cm thick. Titanium was chosen because it has conductivity similar to uranium. One plate was unflawed. The other plate was cut into two pieces. A seam was simulated by pushing the two

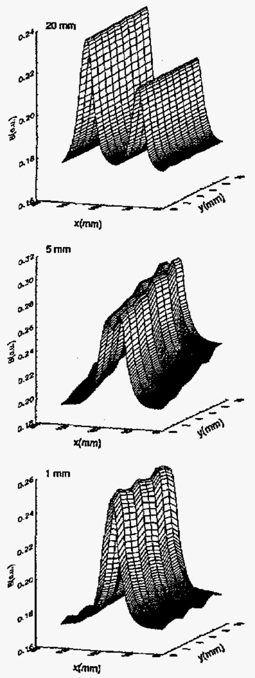

Fig. 7. Scans of Cu plates with scratches at various separations.

pieces together. The seam width was adjusted with spacers. A photograph of this sample is shown in Fig. 8.

Our goal was to obtain quantitative information about the width of the seam while it was buried under 1 cm of unflawed material. Scans were taken for seams of 5, 10, 20, 40, and 60 mils width, at two induction frequencies, 112 Hz and 266 Hz. The results are presented in Fig. 9. The response to the seam appears as a valley in the data. The full-width-at-half-minimum (FWHM) were fit for the valleys and are plotted as a function of seam width. As expected, the amplitude of the response grows with frequency. The lower frequency (112 Hz) appears to show the trend of FWHM vs. seam width most clearly. This is also somewhat expected. At 112 Hz the skin depth is 2.2 cm (recall that the seam is 1 cm beneath a titanium plate). The skin depth for 266 Hz is 1.4 cm. Another interesting feature of the data is that at both 112 Hz and 266 Hz the curve of FWHM as a function of seam width appears to be leveling off. This probably has to do with the width of the seam getting larger than the "field of view" of the SQUID.

IV. Future Directions

A. Modeling and Calibration

We have begun extensive modeling of the titanium seam width problem using, OPERA[4], a commercially available electromagnetic finite element code. We are also using OPERA to design new induction coils that will optimize our sensitivity to features at a particular depth in a sample.

We have also designed a series of copper calibration plates with 75 mm scratches of known depth, width ranging from 0.125 mm to 1 mm. We hope to use data taken with these plates in conjunction with the model to further quantify the resolution of the instrument and the competing

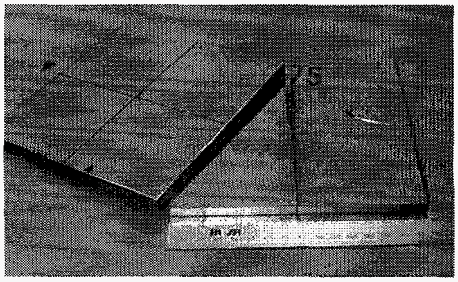

Fig. 8. Photograph of titanium sample. Plates are 150 mm × 150 mm, 1 cm thick. The upper plate is unflawed, the lower plate is in two pieces to create a seam.

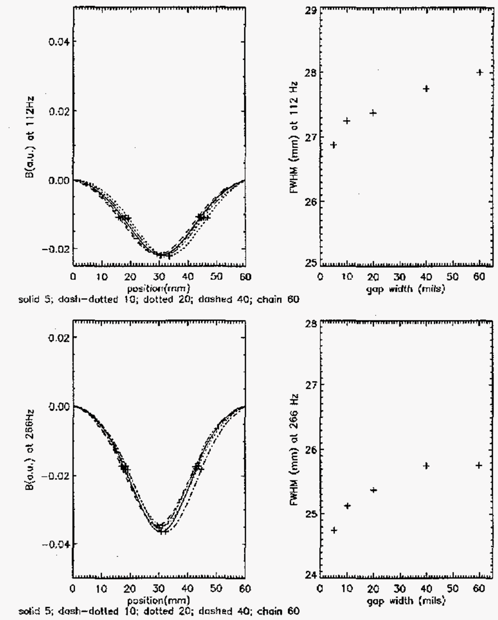

Fig. 9. Data for seams of various widths in titanium plate at 112 Hz, 266 Hz, and 633 Hz. The seams were buried under 1 cm of unflawed plate.

effects of depth and width of scratches (especially when buried under other layers).

B. Expanded Motion Control System and Electronics

In collaboration with Oakridge National Laboratory (a future customer of the milliscope) we are developing a low-magnetic-noise five-axis motion control system that will enable us to examine spherical and cylindrical samples.

Collaborators at Allied Signal/ Kansas City Plant[5] are currently developing high slew-rate flux-locked loop electronics to further the better enable the milliscope's ability to operate in very electromagnetically noisy environments.

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