Non-Destructive Testing (NDT) of Metal Cracks
Using a High Tc rf-SQUID and Eddy Current Method

D. F. Lu, Chang-xin Fan, J. Z. Ruan

Midwest Superconductivity Inc.
Lawrence, KS 66049

S. G. Han, K. W. Wong, G. F. Sun

Department of Physics and Astronomy
University of Kansas
Lawrence, KS 66045

Abstract

A SQUID is the most sensitive device to detect change in magnetic field. A non-destructive testing (NDT) device using high temperature SQUIDs and eddy current method will be much more sensitive than those currently used eddy current systems, yet much cheaper than one with low temperature SQUIDs. In this paper, we present our study of such a NDT device using a high temperature superconducting rf-SQUID as a gradiometer sensor. The result clearly demonstrates the expected sensitivity of the system, and indicates the feasibility of building a portable HTS SQUID NDT device with the help from cryocooler industry. Such a NDT device will have a significant impact on metal corrosion or crack detection technology.

INTRODUCTION

It has been known for almost thirty years since its discovery that a Superconducting QUantum Interference Device (SQUID) is the most sensitive instrument for the measurement of change in magnetic flux, and if used in non-destructive testing (NDT) of materials, it can offer unprecedented sensitivity. It also offers a wide range of frequency response (DC to 10 kHz), which is very important to NDT with eddy current method since low frequency electromagnetic field has a large skin depth and can penetrate deep through a conductor. It was the work of Weinstock and Nisenoff [1] that revealed the first page of such an investigation, in which they demonstrated using a low temperature superconducting (LTS) SQUID that simulated cracks could be detected in ferromagnetic and nonferromagnetic pipes by observing the magnetic field associated with flaws. Thereafter, several research groups joined in to explore this new technology. A LTS SQUID has been used in laboratories for the detection of ferromagnetic rods and plates [2], corrosion in pipes [3,4], naval mines [5], to name a few examples. However, its application in NDT has been proven to be rather difficult to implement. Along with others, the foremost reason is the requirement of a LTS SQUID for liquid helium, which seems not practical for field applications. Hence, the LTS SQUID NDT technology has not been commercially adopted.

The discovery of high temperature superconductors has once again aroused people's enthusiasm for using a SQUID in non-destructive testing in the near future. A high temperature superconducting (HTS) SQUID has the required sensitivity, yet it is capable of working at liquid nitrogen temperature, which is far more advantageous to liquid helium for field applications. The advances in cryocooler industry make it feasible to place a HTS SQUID sensor in a portable cryocooler. Thus, a HTS SQUID magnetometer or

gradiometer has a great potential to satisfy all the four requirements needed in a commercial NDT device, namely: sensitivity, penetration depth, spatial resolution, and device portability. Many efforts have been made to take advantage of HTS SQUIDs. Various types of HTS thin film SQUID magnetometers and gradiometers have been studied [6,7,8,9]. In this paper, we report a different approach we have been using from all previous researches. We proposed [10,11] that a two-hole rf-SQUID be used directly as a gradiometer sensor. In doing so, we eliminate the need for high temperature superconducting flux transformer coils that the conventional design requires. More importantly, we have demonstrated experimentally that this idea works well. Our SQUID has the desired sensitivity, and is capable of working in a noisy environment without magnetic shielding.

EXPERIMENTAL SETUP

The principle is quite simple. It is easy to show that it is the magnetic flux that is measured with a single hole rf-SQUID, but the difference in magnetic fluxes between the holes that is measured with a two-hole rf-SQUID. Suppose that the two holes are aligned in the x direction, with their axes parallel with the z direction, the output voltage of the measuring system, V_{out}, is proportional to the difference of Φ_1 and Φ_2, the magnetic fluxes through the two holes, respectively. If the area A of the two holes are the same, the flux difference $\Phi_1 - \Phi_2$ is then proportional to the mean magne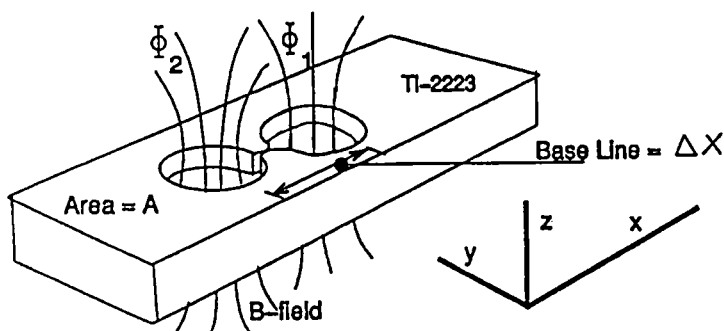tic field difference $\Delta B_z = (\Phi_1 - \Phi_2)/A$. The distance between the two holes, Δx, is the base line length over which the magnetic field gradient $\Delta B_z / \Delta x$ is averaged. Hence it is a natural first order gradiometer. It is insensitive to ambient field interference, yet sensitive to the difference in field between the two holes. Thus it is suitable for NDT field applications since it can eliminate the disturbances from the environment where sources are relatively far from the sensor such that fields generated can be considered uniform over the size of the sensor.

Fig. 1 A double-hole rf-SQUID used as a gradiometer sensor.

Our two-hole rf-SQUID is fabricated on a 3 mm thick Tl-2223 pellet. Two parallel holes of 1 mm in diameter are drilled such that the distance between their centers is 2 mm. A straight thin slot is carved between the holes using a 0.2 mm wire saw until a thin bridge remains right in the middle between the holes. The bridge is then cut carefully until a clear rf-SQUID transfer function pattern is observed [12]. A coil of sixty turns, made from #36 copper wire of about 0.8 mm diameter is inserted into one of the holes. A capacitor of 220 pF is connected in parallel to the coil to form a resonant tank circuit. Finally, model 330 SQUID electronics manufactured by BTi. Inc. and its RF head operating at 19 MHz are used as the measuring equipment. It is experimentally proven that we can operate our HTS rf-SQUID successfully without magnetic shielding, except for the minor shielding from the stainless steel wall of our dewar. Our study also shows that the SQUID has the sensitivity of $10^{-11} T / 2mm / \sqrt{Hz}$.

The apparatus used in our NDT experiment is illustrated in Fig. 2. A liquid nitrogen Dewar with a long thin tail made of stainless steel is used. The rf-SQUID is placed near the bottom of the tail, as close to its bottom as possible since the magnetic field decreases dramatically as the distance between the sensor and the source, in our case the cracks, increases. The test samples we use are aluminum alloy (6061-T6) slabs,
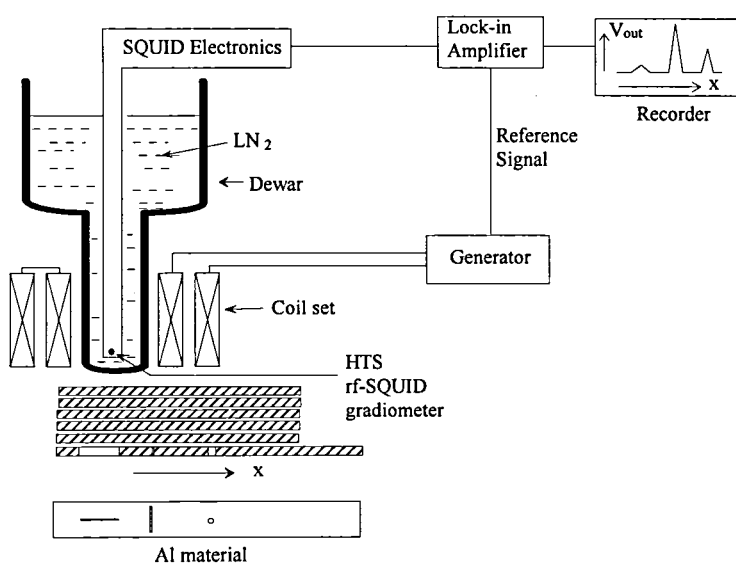
Fig. 2 Sketch of experimental setup

1/8" thick and 2" wide. Several mock cracks of different sizes and shapes are cut in a sample at the bottom of the stack as shown in the figure. This sample is then covered by several pieces of aluminum slabs that do not have defects, and they are pulled slowly under the Dewar tail by a step motor.

In this paper, we adopt the eddy current method. It is very similar to the conventional eddy current method, except that the sensor now is a SQUID that is much more sensitive than coils used in the conventional method. The advantage of this method is that no physical contact with the sample is needed. This may be very important if somehow the conducting sample is covere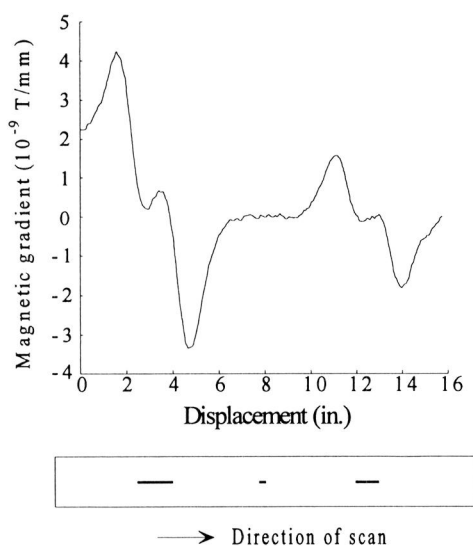d by other non-conducting materials such as paint, cloth, etc. The eddy current method also offers the benefit that the field can be concentrated on only a small part of the sample depending on the size of exciting coils. Thus, there is less restraint on the size of the sample than that for the applied current [10]. To induce eddy current in the sample, two exciting coils are wound and fastened co-axially to the flange on the Dewar tail. The coils are connected in series such that the field at their axes, where the sensor is placed, is very small. The two coils can be moved along their axes for further fine adjustment. Due to the size of the Dewar tail, the diameters of the coils are 1.35" and 3", respectively, which set a limit on the resolution of the system.

In our experiment, the symmetry of the two-hole SQUID is only about 98%, thus leading to a relatively large noise reception. The spectrum of the environmental noise measured by the not-perfectly-symmetric two-holes rf-SQUID shows that the main contributions to noises are from power lines and its harmonics. It also shows minima at 30 Hz and several other frequencies. To eliminate this large environmental noise, we utilize the large dynamic reserve feature of the SQUID system and feed the signal of the SQUID system into a lock-in amplifier for singling out and amplifying the signal that has the same frequency as the supplied field. Then the signal is plotted on a x-y recorder or a computer. If there is no defects in the sample, we would expect a straight horizontal line. However, if there is a crack, a change in field or its gradient would be detected and a peak is generated on the plot. This is the simple illustration of how it works.

EXPERIMENTAL RESULTS

Our first experiment is done with the detection of cracks in aluminum slabs. Several thin slots are cut through a piece of aluminum plate. The lengths of the three slots are: 1-1/2", 1/4", and 1", respectively from left to right as shown in Fig. 3. The width is 1/16" for all the slots. This sample is now covered by 1/2" thick solid aluminum alloy plate, and is displaced 1" from the sensor. The gradiometer sensor is aligned in such a way that the line passing the centers of the two holes is in parallel with the direction of motion. A current of 0.5 mA and 30 Hz is supplied to the set of coils. Fig. 3 clearly demonstrates the sensing capability of our SQUID gradiometer in the presence of environmental interference. Notice that

596

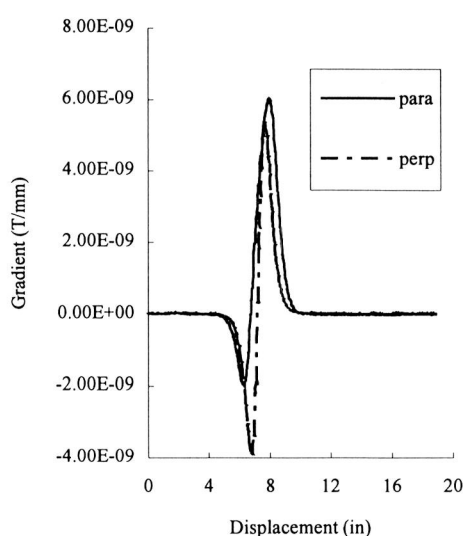Fig. 3 Test result of crack detection.


Fig. 4 Test result of metal presence

there is no magnetic shielding at all; the SQUID is exposed to the external interference. Nevertheless, the signal response is clean and sensitive in general. From the figure, we see clearly the effects of two large cracks (1" and 1-1/2" long). The signals observed clearly shows that the changes in magnetic gradient, in the order of nT/mm, are detected due to the presence of these cracks. However, in this particular test, the smaller crack in the sample does not generate a big enough signals for our system to detect. This is due to the limitation on the resolution of the system as we discussed in the last section. Because of the large sizes of the coils, the field generated does not produce a sharp contrast in a small region. The field cannot be concentrated on a small area to generate a large gradient at the small crack that our sensor is able to measure. This will be solved in our future experiments.

We can also use our SQUID NDT device as a metal detector. Fig. 4 is a plot of detection of the presence of a small piece of aluminum. The size of the piece is 2"×1/2"×1/8". The sample to sensor distance is 1/2", and the sample is not covered any more. In this test, we supply a current of 4.5 mA, 160 Hz to the coil set. We pass the sample underneath the Dewar tail, with its long side parallel with and then perpendicular to the direction of motion. The sensor is still aligned with the direction of motion. The results are shown in the plot and the shape of the curves is expected. It first has a negative peak and then a positive peak. It is interesting to notice that no matter how the sample travels, the amplitude of the signal change and the displacement over which the signal changes are almost the same. For example, the signal changes between position 5 inch and 9 inch on this plot. There is only a slight difference in these positions between the two curves. The peak to peak amplitude of the two curves are almost the same, about 8 nT/mm. This is again due to the poor resolution of the current system.

One of the applications as a metal detector is to detect the distribution of metal objects buried in non-conducting objects, such as re-bars in a piece of concrete. Fig. 5 (a) shows the picture of a piece of such a concrete block, with its front view on the left and the rear view on the right. The concrete is 4" in diameter and 1 foot long. Re-bars of different sizes are randomly buried, with their ends exposed to the surface. The current we supply here is 1 mA and 30 Hz. We scan its side surface and the result is shown in Fig. 5 (b) using a contour plot. Correspondence between the re-bars and the field distribution is immediately shown. The center part of the plot reflect the rear side of the block with only one big spot, while the parts on the left and right, when combined, show the cluster of re-bars at the front. It clearly indicates that the re-bars at the front have a elongated distribution, and its shape shows several maxima where the re-bars are exposed to the surface. By the way, this plot is a plot of field, not gradient. The reason is that our two-hole SQUID
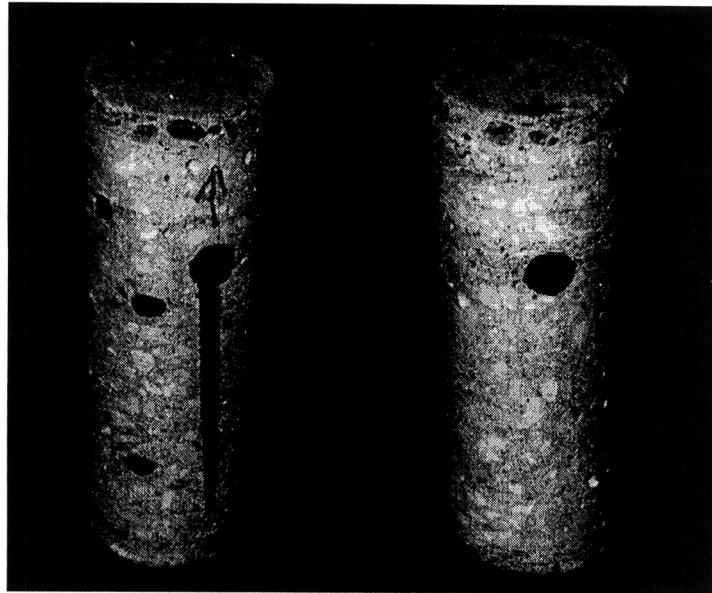
(a)
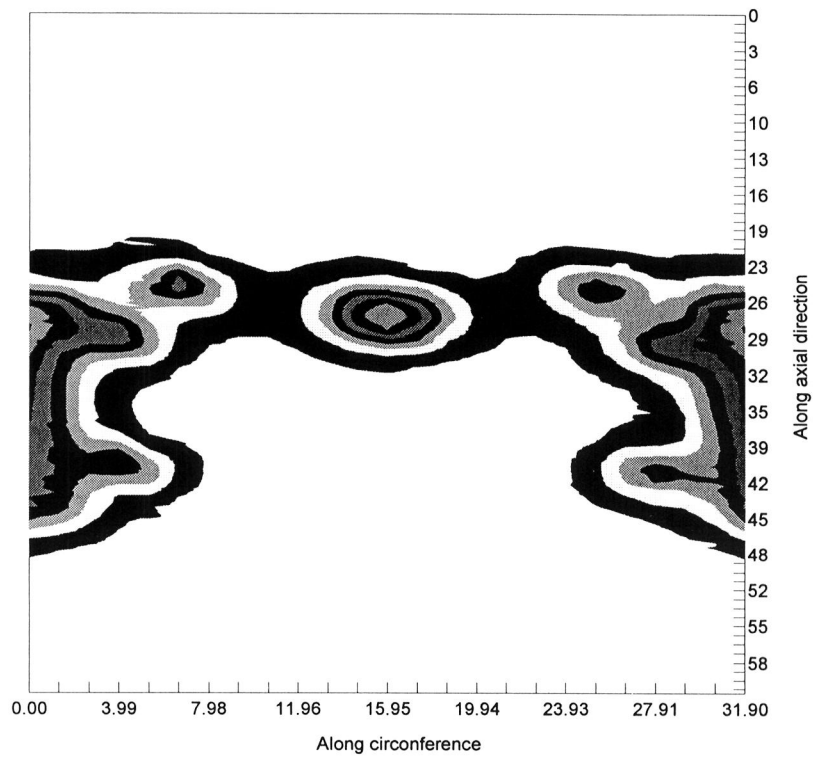
(b)

Fig. 5 (a) Photo of a piece of concrete block with re-bars. The front view is on the left and the rear view on the right. Deep dark areas indicate exposure of re-bars. (b) Contour plot of side surface scan of the concrete. Dimensions are in centimeters.
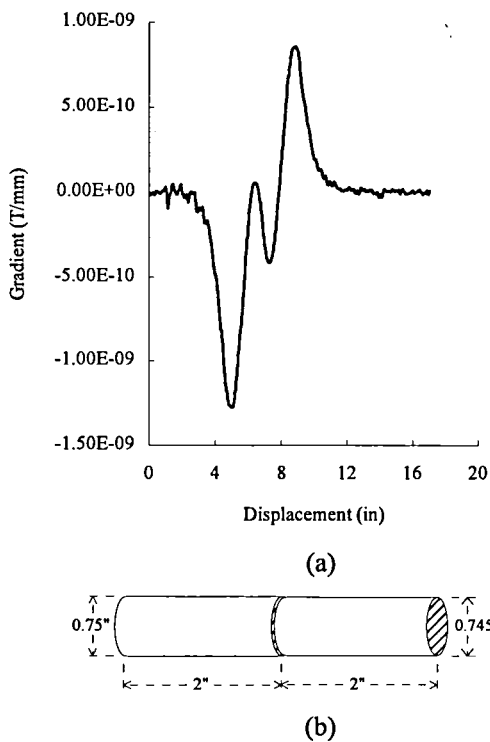
Fig. 6 Corrosion test result.

is not perfectly symmetric as we discussed above. Thus certain amount of field signal will be measured. Since re-bars are ferromagnetic materials, their field is so strong that we have to move the SQUID sensor far from it. The distance between the sensor and the surface of the block is about 1-1/2". Thus the field there, even only 2% appears in the SQUID, is much stronger than its gradient so that field is detected instead. We accept this fact and use the gradiometer as a magnetometer in this test. The advantage of doing this is that environmental noise is already eliminated.

Can we detect corrosion? Yes. Again due to the size of coils, we choose a relatively big piece of brass bar with a diameter of 3/4" and length of 4". Half of the brass bar is corroded with nitric acid vapor. The thickness of the corrosion is only about 0.005". We pass the corroded bar under the SQUID sensor with its length parallel to the direction of motion. The distance between the sensor and the top of the surface is 1/2" and the current supplied is 8 mA and 33 Hz. If it were a uniform long bar, we would expect a curve similar to those in Fig. 4, with no turning back in the middle. However, because of the corrosion, there is a sudden change in thickness and in sample to sensor distance in the middle of the sample. Therefore, a sudden drop in signal happens as it seems to meet another new piece of metal.

In conclusion, we have demonstrated the usage of a HTS rf-SQUID in NDT. Our system, working at liquid nitrogen temperature, does not require any special magnetic shields, nor does it need superconducting transformer coils. Thus, the difficulties associated with making a HTS transformer coil, especially a gradiometer coil, are avoided. The most important feature of our system is its high sensitivity and its ability to measure low frequency signals, which can be utilized to inspect cracks buried deeply inside a conductor. The advance in cryocooler technology makes it very possible to build a portable, practical NDT device. We will work on further improvement of its resolution and portability.

REFERENCES:

1. H. Weinstock and M. Nisenoff, *SQUID '85, Proceedings of the Third International Conference on Superconducting QUantum Devices*, H. D. Hahlbohm and H. Lubbig, eds., de Gruyter, Berlin, 843 (1985)

2 R. J. P. Bain, G. B. Donaldson, S. Evanson, and G. Hayward, *SQUID '85, Proceedings of the Third International Conference on Superconducting QUantum Devices*, H. D. Hahlbohm and H. Lubbig, eds., de Gruyter, Berlin, 841 (1985)

3 J. C. Murphy, G. Hartong, and R. F. Cohen, *J. Electrochem. Soc.* **135(2)**, 310 (1988)

4   J. C. Murphy, R. Srinivasan, and R. S. Lillard, *Review of Progress in QNDE*, D. D. Thompson and D. E. Chimenti, eds., **8b**, 2149, (Plenum, NY 1989)

5   P. V. Czipott and W. N. Podney, *IEEE Trans. on Mag.* **Mag-25**, 1204 (1989)

6   R. Kromann, J. J. Kingston, A. H. Miklich, L. T. Sagdahl, and John Clarke, *Appl. Phys. Lett.* **63**, 559 (1993).

7   L.P. Lee, K. Char, M.S. Colclough, and G. Zaharchuk, *Appl. Phys. Lett.* **59**, 3051 (1991).

8   B. Oh, R. H. Koch, W. J. Gallagher, R.P. Robertazzi, and W. Eidelloth *Appl. Phys. Lett.* **59**, 123 (1991).

9   M. N. Keene, S. W. Goodyear, N. G. Chew, R. G. Humphreys, J. S. Satchell, J. A. Edwards, and K. Lander, *Appl. Phys. Lett.* **64**, 366 (1994).

10 Chang-xin Fan, D. F. Lu, K. W. Wong, Y. Xin, B. Xu, N. S. Alzayed, M. Chester, and D. E. Knapp., *Cryogenics*, in press.

11 Naser S. Alzayed, Chang-xin Fan, D. F. Lu, K. W. Wong, Marvin Chester, and David E. Knapp, *IEEE Trans. on Appl. Superconductivity*, **4**, 81 (1994).

12 S. Harrop, C.E. Gough, M.N. Keene and C.M. Muirhead, *Physica C* **153-155**, 1411 (1988).