EVOLUTION OF THE CRYOGENIC EDDY CURRENT MICROPROBE

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INTRODUCTION

In nondestructive eddy current testing (ET), wire coils are excited to induce electric currents in conducting test specimens. The distribution of these eddy currents is altered by the presence of flaws in the material or by changes in material properties. The distribution changes are then sensed by one or more detector coils.

Because of industrial requirements for longer inspection intervals and the increased use of high-strength, brittle materials, ET techniques are needed with greater flaw sensitivity and characterization ability to enhance the spatial resolution of the ET probes, which can be accomplished by using smaller probe coils. The trade-off for smaller coils is reduced signal strength. To compensate for the signal loss, low-noise superconducting probes with cryogenically operated electronics are being developed. These extremely small, sensitive probes can be made practical by using the latest results of research in high-temperature superconducting technology, in particular Josephson junction devices such as Superconducting Quantum Interference Devices (SQUIDs).

The primary objective of the work reported here was to develop small, normally conducting eddy current probes with ultra-high resolution that functioned at 77 Kelvin (K), the temperature of liquid nitrogen. The probes consisted of a hybrid electronics package including a sensing-coil array and preamplifier electronics mounted on a single substrate with an excitation coil. Development of fabrication techniques adaptable to the use of SQUID detectors was part of the project.

A secondary objective was to develop thin-film and hybrid techniques for eddy current probe production. The purpose was to allow fabrication of probes with more precisely controlled and repeatable geometry and electromagnetic characteristics than is possible with present labor-intensive wire-wound coil fabrication techniques.

In this program, two types of sensor elements were designed and built. One utilized photolithography, described in a previous paper [1]. The other used ion-beam milling techniques. The ion-beam-milled sensor has a higher inductance per square millimeter due to the smaller line

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 9
Edited by D.O. Thompson and D.E. Chimenti
Plenum Press, New York, 1990

width and increased number of turns per square millimeter. This paper reports on results of the ion-beam milled sensor.

PROBE DESIGN

The probe consisted of an encircling exciter coil, differential detector coils, and hybrid amplifiers for each of the detector coils. The sensors and amplifiers were mounted in a TO-5 component carrier approximately 6 mm in diameter. The component carrier was surrounded by a cooling jacket for operation at liquid nitrogen temperature.

Electronics

The probe electronics were mounted on three main substrates at different levels in the carrier. Each sensor coil consisted of a spiral pattern machined out of a gold-chrome thin film deposited on an aluminum oxide substrate, as shown in Fig. 1. The coil substrates were mounted on the probe lower substrate, as shown in Fig. 2. This technique protected the sensor coils, but created approximately 0.5 mm of liftoff due to the probe substrate thickness.

A prototype dual-channel, four-stage J-FET amplifier was designed and built using conventional electronic components. Then the first stage was miniaturized with hybrid components and placed on three alumina substrates. The first stage was designed to have a 10-dB gain to boost the sub-microvolt signals. The interconnect cable between substrates was part of the tuned circuit of the amplifier. This packaging technique placed the amplifiers within 1 mm of the sensors.

The total substrate diameter was less than 6 mm. The lower substrate contained two sensors, two capacitors, and four resistors. Two other substrates had a total of 12 components required to tune and control the two amplifiers. These amplifiers were tuned to 2 MHz. The total gain of the amplifier was 80 dB, which yielded a -50 dB gain for the total driver pickup system.

Cooling

Two methods of cooling the probe were considered. One method involved passing the cooling gas over the outside of the substrate that formed the wear face between the sensors and the specimen, and the other involved passing the cooling gas over the component side of the substrate. Calculations of the cooling requirements to maintain the sensors at 77 K when the wear face was within 0.05 mm of the room-temperature specimen were 2 watts and 0.01 watts, respectively, for the methods described previously. Due to the volume and velocity of gas required to obtain 2 watts of cooling, the second method was selected. Some exterior cooling was provided by the gas-lubricated hydrostatic bearing between the sensor package and the sample. The majority of the cooling was provided by the absorption of heat to the liquid through the sensor package housing. A cross section of the sensor assembly and cooling jacket is shown in Fig. 3.

Gas Bearing

The sensor assembly, which included the probe, cooling jacket, and electronics, was designed to provide a gas-lubricated hydrostatic bearing between the wear face of the probe and the surface. This bearing was required to insulate the cooling jacket from the specimen and prevent ice formation between the specimen and the cooling jacket. The gas bearing

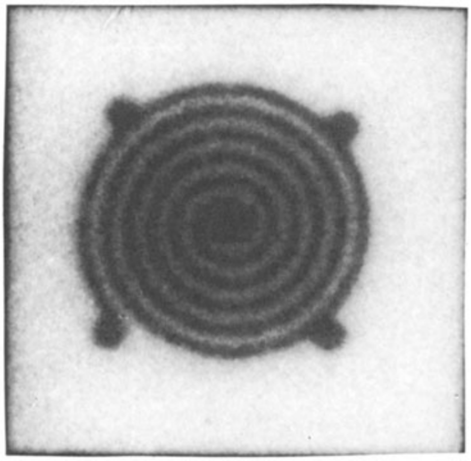

Fig. 1. Chip inductor used as a sensor for second-generation hybrid sensor array. This sensor was made using ion-beam milling methods and had five turns in a 0.58 square mm area.

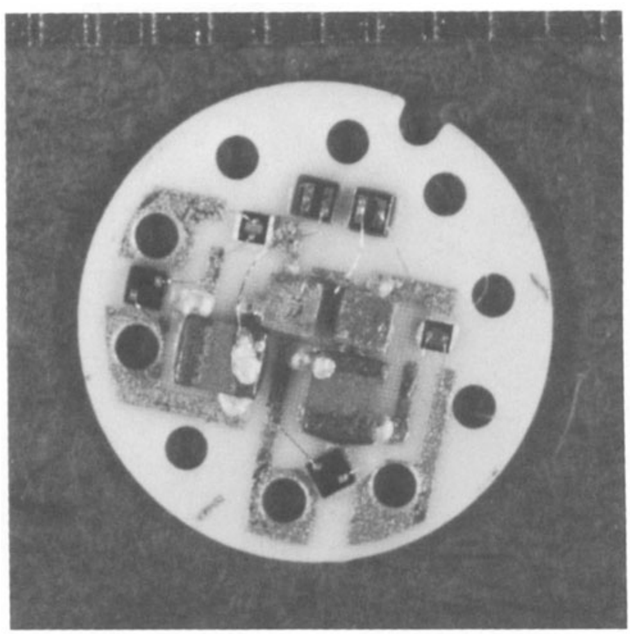

Fig. 2. Lower substrate of hybrid electronics. Two channels are present on the substrate.

was designed to maintain a constant pressure loss produced by the orifice in the gas source. The source of the gas was the chamber formed by the shielding canister for the electronics. The orifices were two 0.5 mm diameter ports in the wear face of the lower substrate.

This cavity of higher pressure gas provided a load-carrying capability of 0.1 Newton at a liftoff of 0.04 mm, with a pressure of 13 psi supplied through the substrate. In the actual experiment at 70 K, the increased density of the cold gas produced a gas bearing with a liftoff of 0.13 mm. The bearing generated at the lower temperature exerted a correspondingly larger force of 0.24 N on the specimen.

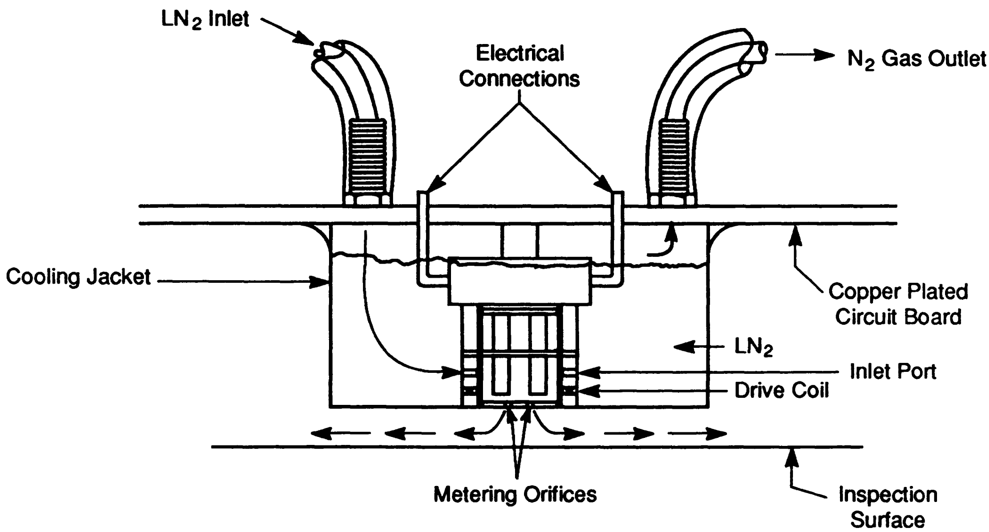

Fig. 3. Cross section of sensor package and cooling jacket

INSTRUMENTATION

A block diagram of the experimental setup used during the warm and cold testing of the eddy current probe is shown in Fig. 4. The eddy current probe and lower stage amplifier combination, as well as the upper stage amplifier, were mounted in a precision two-axis scanner controlled by a Compumotor C3000 indexer. The test specimen, made of IN-100 material and containing five EDM notches, was securely fastened beneath the eddy current probe.

The test instrument used to excite and monitor the eddy current probe was an HP 4194A impedance analyzer operated in the gain-phase, driver-pickup mode; that is, the output of the integrated amplifier was connected to the input (pickup) and the exciter coil of the probe was connected to the output (driver). An external amplifier was used on the

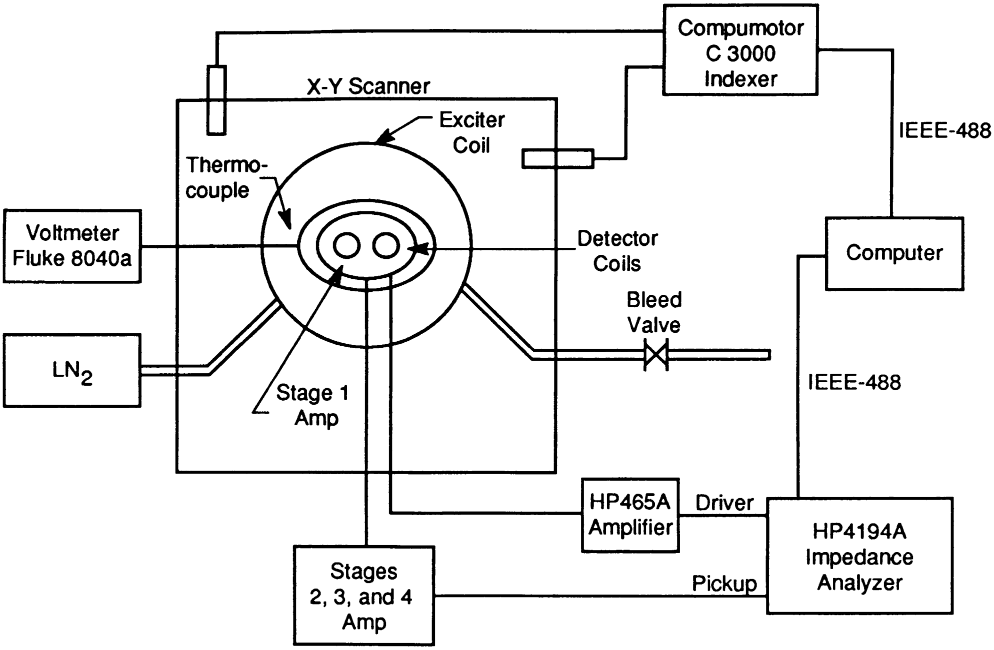

Fig. 4. Block diagram of experimental layout used to test the microprobe

output of the impedance analyzer to boost the signal to the exciter coil. An IBM-PC AT-compatible computer was used to control both the HP 4194A and the C3000 indexer via an IEEE-488 interface bus. Data were stored on the Sun fileserver for post-acquisition analysis.

For the tests with liquid nitrogen, a small K-type thermocouple was inserted in the amplifier housing to measure the temperature of the amplifier and probe coils. The voltage output of the thermocouple was monitored with a Fluke 4115 precision voltmeter.

EXPERIMENTAL RESULTS

The data from the experiments were scaled and bandpass-filtered to remove high-frequency noise and low-frequency drift. The data were then displayed using one of two methods: 2-D display of the data scans as shown in Fig. 5, and 3-D pseudo-color display.

The 2-D display allowed the quality, the spatial resolution in the X-direction, and the magnitude of the data response to be evaluated. Measurements of the signal-to-noise ratio (SNR) can also be made from the data in this format since the high-pass filter has removed the low-frequency components that originally separated the scans before normalization.

The 3-D display provides the data from the 2-D scan in addition to the information on the spatial resolution in the Y-direction. The color display also provides for the rapid identification of defective areas as

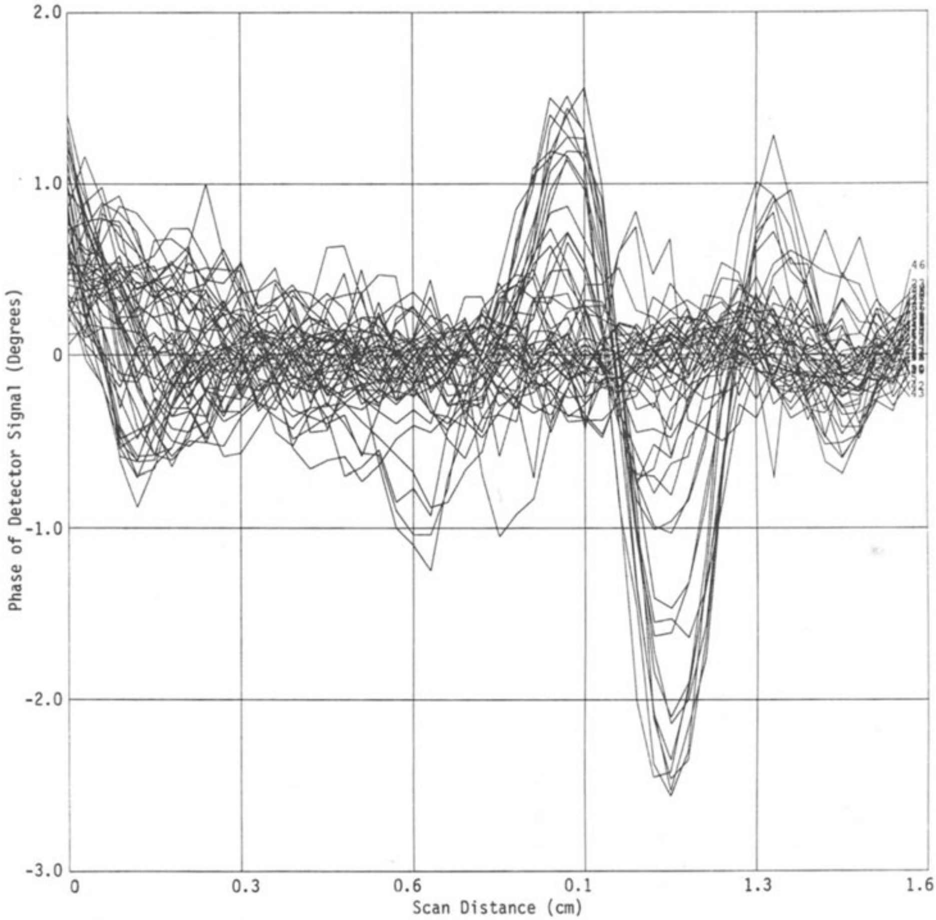

Fig. 5. 2-D display used to analyze the spatial frequency in the X-direction and magnitude of the flaw response. These data were taken on flaw C under room-temperature conditions.

shown in Fig. 6. The color signal processing algorithms provide a means for a two-dimensional interpolation of the data, so that after the filter has been applied the data are reconstructed in a format more similar to the actual eddy current surface distribution, instead of displaying only the values at points sampled along the surface. In these algorithms the original points are retained, but additional points are added between points to smooth the transitions.

An IN-100 specimen with EDM notch flaws (see Table 1) was used for probe testing. Data were taken on flaws A through F at room temperature in absolute mode using one detector coil; the other coil's electronics had failed. Flaws B through F were easily detectable, but the response from flaw A was hard to distinguish from the background noise. Fig. 6 shows the response from flaw B.

Experiments with the probe at liquid nitrogen temperature were conducted on flaws C through E. These tests resulted in flaw responses similar to those from the room temperature tests. Because the gas bearing liftoff changed with temperature, it was difficult to directly compare the response at the different temperatures. For example, changing

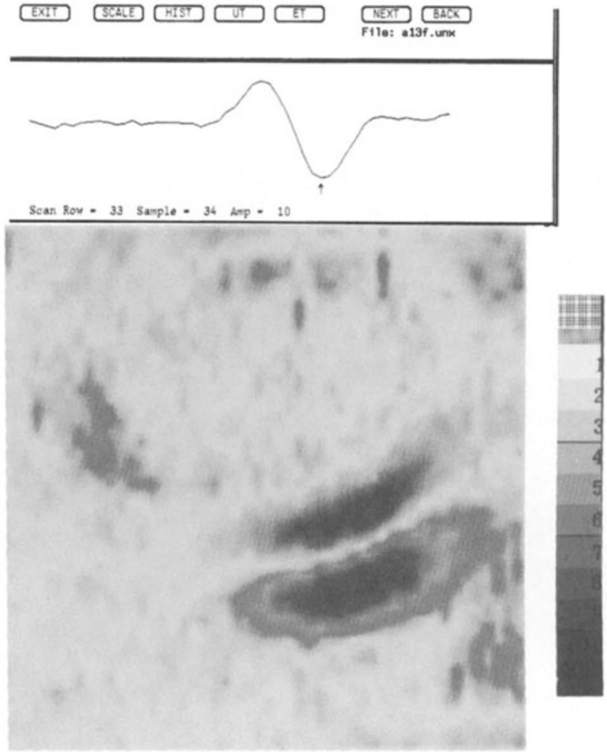

Fig. 6. Gray scale plot looking perpendicular to the surface showing X and Y extent of the flaw. These data were taken on flaw B under room-temperature conditions.

Table 1

EDM NOTCHES IN IN-100 SAMPLE

Flaw	Depth (mm)
A	0.13
B	0.25
C	0.51
D	0.89
E	1.27

Notch Length = 0.050 inch
Notch Width = 0.003-0.005 inch

the gas temperature from room temperature to liquid nitrogen temperature increased the gas bearing thickness from 0.03 to 0.25 mm. The gain of the cooled electronics also changed, with the difference being less than 0.5 dB at the two temperatures. Some of this measured difference may be due to changes in inductance and coupling of the exciter and detector coils.

CONCLUSIONS

A thin-film eddy current probe was successfully manufactured and operated at room temperature and liquid nitrogen temperature. Several conclusions were drawn from the experiments:

- The sensor package design was sufficient to maintain the detector and electronics at 77 K, with a distance of less than 1 mm above an uncooled specimen.
- Ice formation between the sensor package and the inspection specimen was successfully avoided.
- The spatial resolution of the probe did not exceed conventional eddy current probe capability, probably because of a relatively large operational liftoff. Modification of the detector coil placement will be required to realize the potential of this approach.
- Manufacturing techniques were demonstrated that can be extended to much smaller detector coil sizes with even greater numbers of turns.

REFERENCE

1. J. L. Fisher, S. N. Rowland, F. A. Balter, J. S. Stolte, and K. S. Pickens, "A Cryogenic Eddy Current Microprobe," *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 8A, edited by D. O. Thompson and D. E. Chimenti, Plenum, 1989, 959-965.