A 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 than those currently in use. One way to improve flaw characterization is 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 subject work was to develop small normally conducting eddy current probes with ultra high resolution that functioned at 77 Kelvins (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 photolithographic techniques for eddy current probe production. The purpose was to allow fabrication of probes with precisely controlled and repeatable geometry and electromagnetic characteristics.
SYSTEM DESCRIPTION

A breadboard system was assembled. The experimental layout, illustrated in Fig. 1, included a reflection eddy current probe with photolithographically produced, differential probe coils and a low-noise, high-gain, low-temperature amplifier.

Probe

The probe coil consisted of the substrate, component carrier, and external case, which were potted together using a low thermal-expansion coefficient epoxy to form a single assembly. The substrate was composed of a PR-5 thermoset, resin-fiberglass board with a conductive pattern photolithographically deposited on one surface. The pattern, shown in Fig. 2, had two square, spiral patterns side by side. These patterns were completed into current loops using a jumper wire from the center of the pattern to the outside connector pad. The jumper was 0.05 mm in diameter. Insulation of the jumper was accomplished by applying a non-conductive layer 25 microns thick onto the tracks over which the jumper would pass. Then the wire was soldered using a soldering tool with a 0.075-mm diameter tip. An additional jumper was placed on the backside of the circuit board to provide for symmetric spacing of the support pins.

This construction technique allowed a minimum 0.125-mm liftoff distance from the test surface to the substrate surface. The potting compound also functioned as a wear face to protect the probe while scanning.

A standard TO-5 component carrier with eight pins was modified to accept the substrate by removing four pins and adjusting the pin height. When the substrate subsequently was placed on the four pins with the ends of the pins at the front surface, the substrate was parallel to the bottom of the component carrier and recessed 0.15 mm from the end of the external housing.

The external housing of the probe was made of kovar metal to provide electric shielding and a low coefficient of thermal expansion. The outside surface of the external housing was also used as a surface against which the exciter coil would ride. The exciter coil was mounted on the outside of the case and held in place by a spring attached to the probe assembly. The spring allowed the coil form and external housing to move relative to each other during cooling.

Amplifier

A four-stage JFET amplifier was developed for this probe. Components were chosen for low noise, compatibility with low-temperature operation, and availability in die form to allow conversion to a hybrid form.

The first two stages were operable at a temperature of 77K with little change in gain or noise at 300K (room temperature). The amplifier was adjusted for maximum gain at 2 MHz with a 3-dB bandwidth of approximately 1 kHz. The voltage gain of all stages together was over 10,000 at room temperature. With these conditions, the noise level at room temperature was 0.5 μVolts. The bandwidth could be further reduced to lower the noise level. (Conventional eddy current instruments typically operate with 100 to 200-Hz bandwidth.)
Fig. 1. Experimental layout used to test the microprobe

Fig. 2. Breadboard two-coil array shown mounted on an eight-lead, TO-5 transistor case. Width of the sensor-coil array was approximately 40 mils.
Exciter Coil

The exciter was a single coil encircling the probe-coil array. It consisted of 30 turns of 36 AWG enameled magnet wire, which had a mean diameter of 9.08 mm, a cross-sectional area of 0.48 mm², and a 20.97 mm square surface area normal to the probe. It was built on a phenolic material with a coefficient of thermal expansion similar to that of the probe substrate.

The linear thermal-expansion coefficient for the exciter coil material was $2 \times 10^{-5}$ cm/cm/degree Centigrade in contrast to $5.86 \times 10^{-6}$ cm/cm/degree Centigrade for the Kovar case material. This difference in thermal-expansion coefficients required the clearances at room temperature to be adjusted by a factor of 0.293. The clearances were regulated to room temperature so that the coil form-to-external case clearances were 0.05 mm at 70K.

Experimental Setup

A block diagram of the experimental setup used during the initial testing of the eddy current probe was shown in Fig. 1. The eddy current probe and the four stages of the JFET amplifier were mounted in a precision two-axis scanner. Fig. 3 shows the completed probe. The test specimen, made of IN-100 material and containing a 0.13-mm wide by 1.27-mm long by 1.27-mm deep notch, was securely fastened beneath the eddy current probe. The two receiver coils of the probe were connected in a differential configuration and were the input for the first stage of the JFET amplifier. The test instrument used to excite and monitor the eddy current probe was an HP 4194A impedance analyzer. The impedance analyzer was operated in the gain-phase, driver-pickup mode; that is, the output of the JFET amplifier was connected to the input (pickup) and the eddy current exciter coil was connected to the output (driver). An IBM-PC AT compatible computer was used to control both the HP 4194A and the two-axis scanner via an IEEE-488 interface bus.

Results

Using the experimental configuration described above, two-dimensional scans were taken on the IN-100 sample. A 25.4-mm square area around the notch was examined with a raster-scan pattern consisting of fifty linear scans, each with fifty points. The results of a typical raster scan are shown in Fig. 4. Fig. 4a shows the gain component of the received signal, and Fig. 4b shows the phase component of the same signal. In both figures, the differential flaw response is clearly visible.

Future Direction

The ultimate goal of this effort is to produce a superconducting eddy current microprobe, which is being approached via a phased project. The first phase was just described. The next phase will involve the implementation of the cryogenic amplifier using hybrid-circuit technology. This type amplifier will support the integration of multiple coils and amplifiers to produce an array; the array, in turn, will allow high-speed, high-resolution eddy current data acquisition for eddy current imaging.

For the next phase, both high-temperature superconducting shields to reduce noise pickup and a reduction in the size of the coils/amplifiers will be required. These two enhancements complement each other with the noise reduction from the superconducting shields offsetting the reduction...
Fig. 3. Completed probe examining a test specimen
Fig. 4. Two-dimensional scans at 2 MHz of a 1.27 x 1.27-mm notch in a IN-100 material specimen. The upper plot displays the phase; and the lower, the gain.
in signal caused by scaling the coils. It is anticipated that the signal-to-noise ratio will remain constant or somewhat improve.

The third and final phase of the effort will involve replacing the conventional coils with a superconducting version and adding a superconducting detector. It is expected that the sensitivity of such a detector will be limited by environmental noise pickup.

CONCLUSION

A breadboard probe was assembled and successfully tested. The probe consisted of the probe coil array, exciter coil, and preamplifier—all mounted on a copper plate. This version of the probe coil array has a two-coil pattern deposited on a fiberglass substrate. The coil array has approximately 25-micron (1-mil) line widths and 100-micron (4-mil) line separation. The substrate was mounted in a standard 8.1-mm diameter TO-5 transistor package.

The low-noise preamplifier used in the probe had a total voltage gain of 10,000. The first two stages, designed to be incorporated in hybrid form into the probe, were successfully tested at liquid nitrogen temperature.

Initial tests confirmed that the probe could be used for flaw detection. Successful detection of 1.25-mm long electrodischarge-machined (EDM) notches in IN-100 with the probe operated in both absolute and differential modes was demonstrated.