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Non-Destructive Testing using a HTS SQUID

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***Abstract*—We have used a high temperature superconductor (HTS) SQUID in an unshielded environment to perform eddy current nondestructive testing measurement of a multi-layer aluminum structure. The sensor consists of an YBCO dc superconducting quantum interference device (SQUID). As a demonstration of the system's capabilities, subsurface defects in a multi-layer aluminum structure have been located and mapped using eddy current with no magnetic shielding around the specimen.**

***Index Terms*— high temperature superconductor, multi-layer aluminum structure, nondestructive testing, SQUID.**

I. Introduction

Conventional nondestructive testing is a well established technique that is used routinely to locate and characterize flaws in various structures, such as aerospace, marine, nuclear and high-pressure vessels. One of the outstanding applications in nondestructive testing is the reliable detection of deep sub-surface flaws that may be caused by corrosion and fatigue in multi-layer structures. This is a particular problem in nondestructive testing of aircraft where a method is needed to detect flaws that occur in layers of aluminum around rivets without the removal of paint or disassembly of the part. Although many researchers have used SQUIDs for nondestructive testing of aircraft and other structural systems and materials, most of them were done in a magnetically shielded room to reject the background noise [1][2][7][11][18].

In this report, we have made an eddy current nondestructive testing of a multi-layer aluminum structure using the HTS SQUID in an unshielded environment.

II. Experimental Procedure

The nondestructive testing system consists of a HTS SQUID in a fiberglass dewar and magnetically quiet x-y scanning system.

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The dc SQUID is made from $YBa_2Cu_3O_7$ film, and has a washer structure with multi-loop pick-up coils. The intrinsic noise power spectral density of the bare SQUID is 25.5 $\mu\Phi_0$ $Hz^{-1/2}$ at 10 Hz measured in a magnetic shield case. Its pick-up coils occupy an effective area of 0.08 mm^2. Fig. 1 shows the geometry of the scanning system. The HTS SQUID device has been operated in a 0.4 liter fiberglass dewar with a hold time of over 6 hours. Minimum spacing of dewar's tail is 2.5 mm. The HTS SQUID is held horizontally and is operated in a conventional flux-locked loop with a modulation frequency of 40 kHz. Table 1 shows the parameter of the HTS SQUID operated outside of a magnetic shield room. The value of field sensitivity is set for a small value (52.6nT/V) compared with a conventional operating conditions (1.4nT/V) to reduce the perturbation by noise. The SQUID device is placed in an aluminum cylindrical tube with slots to reduce rf interference. The dewar is suspended on a non-magnetic frame above a computer controlled, magnetically quiet x-y scanning system [3][4][13]. This system is located in a conventional research laboratory, with nearby computers, power wiring and other disturbances. Fig. 2 shows a magnetic flux noise spectrum measured with our HTS SQUID. There are several noise peaks which originate from power lines (50 Hz and 100 Hz) and computers (20Hz and 30 Hz). There is a magnetic flux of 70 Hz from a eddy current coil (a double-D coil). The noise power spectral density of the SQUID increased to 52pT $Hz^{-1/2}$ at 10 Hz compared with 0.6pT $Hz^{-1/2}$ which is calculated from the noise power spectral density of the bare

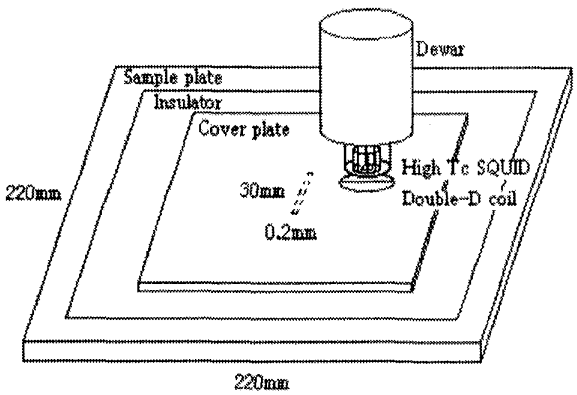

Fig. 1. The geometry of the scanning system.

SQUID in a magnetic shield case; 25.5 $\mu\Phi_0$ $Hz^{-1/2}$ and an effective area of pick-up coils; 0.08 mm^2. Fig. 3 shows a photograph of a plastic dewar and the non-magnetic frame. An 18 μm layer of aluminum foil is wrappe around the dewar to reduce rf interference. Fig. 4 shows a cross sectional model of the tail of the dewar and the test sample plate. Eddy currents were induced in the test sample by a 5 turn, 50 mm diameter copper double-D coil. A center of the double-D coil was coincided with a central axis of the pick-up coils of the SQUID in z direction. The double-D coil was positioned 3 mm above the sample and 5 mm below the lower edge of the SQUID.

When the eddy current was induced in a uniform test sample, a symmetrical magnetic field with respect to the central axis of the pick-up coils was generated, and the output signal of the SQUID was very small. If there was a flaw in the test sample, an asymmetrical magnetic field was generated, and detected with SQUID. The minimum size of a flaw which can be detected with the pick-up coils should increase with the size of the pick-up coils in x-y (horizontal) direction, and decrease with the distance between the sample and the pick-up coils. The subsurface flaw's depth detected with the pick-up coils was limited by the skin depth of the cover layer of the test sample. A current of 70Hz was applied to the coil.
The conductivity of aluminum at this frequency is 18.1 MSm^{-1}, giving a skin depth of 14.1 mm.

III. RESULTS AND DISCUSSION

The system has been used to scan multi-layer aluminum samples (JIS H4000 aircraft grade A110P-H14). As an example we have examined a 10 mm thick plate with a

TABLE I

Parameter of HTS SQUID operated outside of a magnetic shield room
Effective area of pick up coil : 0.08 mm^{-2} Field sensitivity : 52.6 nT/V Noise power density : 52 pT $Hz^{-1/2}$

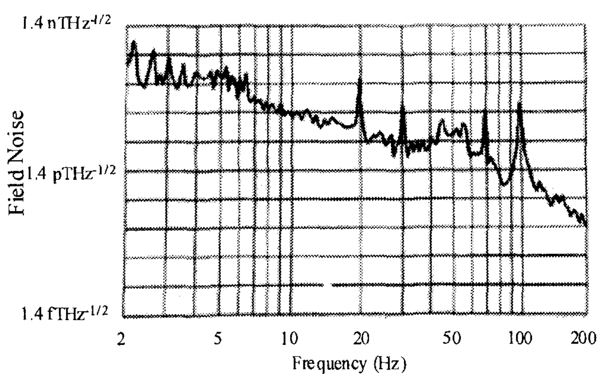

Fig. 2 . A magnetic flux noise spectrum measured with High Tc SQUID.

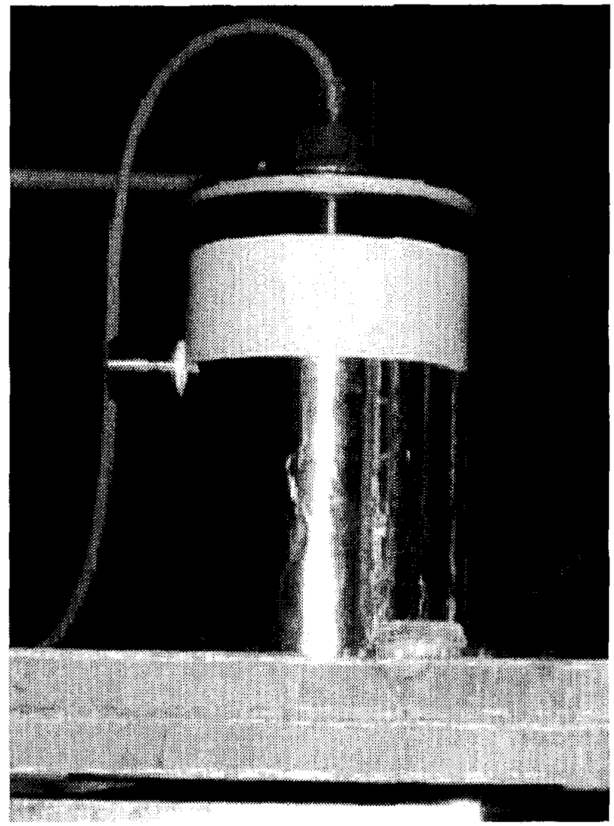

Fig. 3 . A photograph of the plastic dewar and the non-magnetic frame.

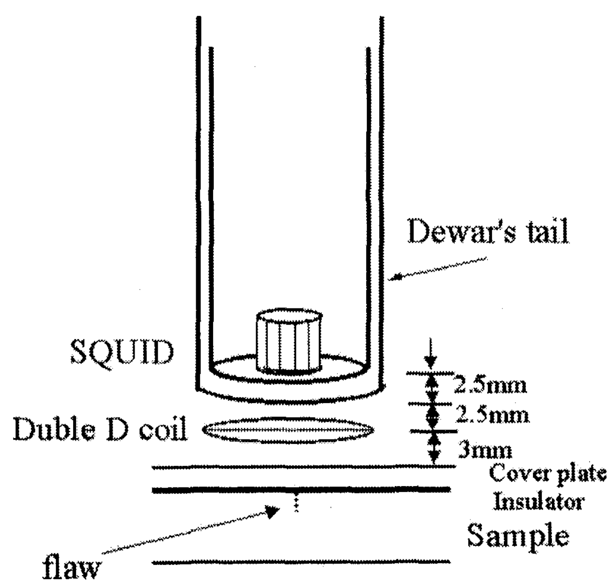

Fig. 4 . A cross sectional model of dewar's tail and the test sample plate.

machined flaw 0.2 mm wide and 30 mm long on its top surface, covered with a 0.08 mm layer of insulator and then with a 1 mm layer of aluminum. The axis of the double-D coil is at a right angle with the flaw. The sensor was scanned at a speed of 3.3 mm/s.

A magnetic field signal sensed by the SQUID was lock-in detected with a reference of the coil current. A 10 mA rms current at 70Hz was applied to the double-D coil, giving a vertical magnetic field of 5 μT at the sample surface.

The resulting 2D image of the unprocessed SQUID output signal is shown in Figure 5 which is a mapping result of the detected magnetic field strength. In order to reveal a polarity of the magnetic field, it is shown in a pseudo 3D graph, background is at zero level.

When the eddy current was induced in a uniform test sample, a symmetrical magnetic field with respect to the central axis of the pick-up coils was generated, and the output signal of the pick-up coils was very small. If there was a flaw in the test sample, an asymmetrical magnetic field (nT order) was generated, and detected with the pick-up coils. At the end-point of the flaw, the detected signal became maximum, because the asymmetry of the magnetic field distribution became maximum. These corresponds to two pairs of white and black circle patterns in Fig.4. The center of the white and black pattern corresponds the end-point of the flaw.

There are frequent bursts of rf detected by the SQUID as equipments in the building are switched on and off. An aluminum cylindrical tube with slots was used to reduce the bursts of rf noise.

IV. CONCLUSIONS

A HTS SQUID was used to perform eddy current nondestructive testing measurements on a multi-layer aluminum structure in an unshielded environment. The performance has been found more than adequate to locate certain flaws in a multi-layer aluminum sample which simulate the defects in aircraft.

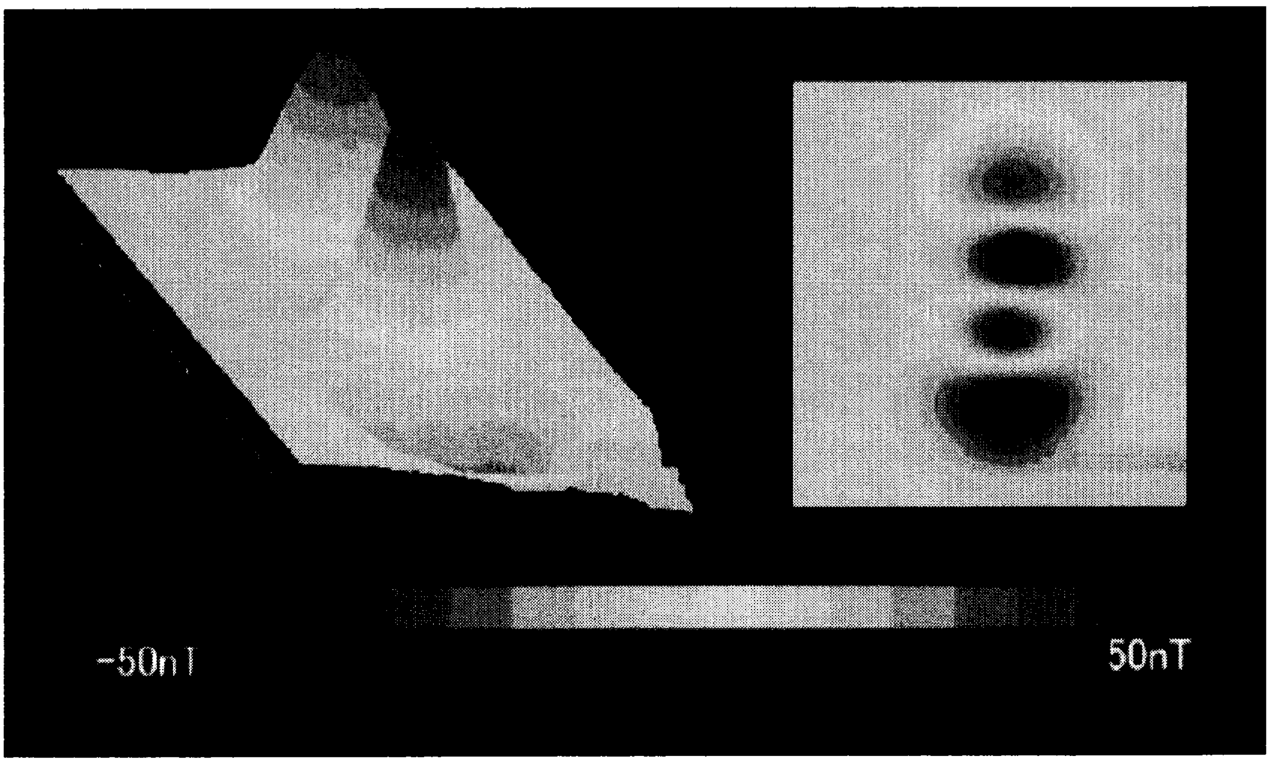

Fig. 5. 2D scans of a multi-layer aluminum sample. The scanning area is 100x100 mm.

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