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Non Destructive Testing (NDT) With High Tc RF SQUIDS

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Abstract. A high Tc rf SQUID nondestructive evaluation (NDE) set-up has been realized to measure the eddy current induced field in different aluminum samples, under a weak AC and low frequency magnetic excitation. An efficient and simple analytic modeling method has been also developed for computing the magnetic field created by the induced eddy current in the samples and compare it with experimental results. The modeling results for different samples with various calibrated defects correlate well with the experimental data obtained with the rf SQUID gradiometers in an unshielded environment.

1. Introduction

Superconducting Quantum Interference Devices (SQUIDS) are the most sensitive magnetic sensors. SQUIDS based on the high Tc superconductors require only cooling down to liquid nitrogen temperature. They offer a high sensitivity ($10\text{-}100 \text{ fT Hz}^{-1/2}$) at low excitation frequencies permitting the detection of deeper defects, broad dynamic range ($> 80 \text{ dB}$) and a high linearity, allowing quantitative evaluation of magnetic field maps from the investigated structure [1, 2].

Aluminum based advanced composites are widely used in different aircraft structures and components. High performance NDE methods will be of great utility for these types of materials. Because of its high sensitivity, SQUID magnetometry is a promising NDE method to detect defects in the diamagnetic and paramagnetic materials [3, 4]. In this report, the description of the SQUID NDE instrumentation for measuring the eddy current induced field in aluminum samples and the principle of an efficient and simple modeling method are described.

2. Experimental set-up

Our high Tc rf four-SQUID gradiometer system has been developed by JSQ company at Juelich and it has the following specifications: sensitivity $6.9 \text{ nT}/\Phi_0$, white noise $70 \mu\Phi_0/(\text{Hz})^{1/2}$, washer dia. 3.5 mm , loop $150 \times 150 \mu\text{m}^2$, operating frequency approx. 800 MHz , individually staggered for each SQUID. The system provides a $\pm 10 \text{ V}$ signal proportional to the measured field gradient. Therefore, the high sensitivity of this magnetic sensor allows to obtain a voltage-per-field-coefficient as high as

4.06V/ μ T. The structure has been made mainly of plexiglass and also other non magnetic materials as brass, copper, Al or wood in order to avoid any magnetic noise (figure 1). The samples are moved underneath the gradiometer by means of a two-axis x-y scanning stage. The stage and the data acquisition are controlled with a LABVIEW program which is optimized to automate the entire measuring process. An AC excitation signal of 1 V peak to peak (pp) and 180 Hz applied to the Helmholtz coils, corresponds to a magnetic field amplitude of 0.12 G (pp). A lock-in amplifier has been used to achieve a synchronous detection. The signal amplitude has been adapted to the different samples of various sizes. The scanning has been perpendicular to the width of the samples. Aluminum samples have been provided by the US Air Force in the form of sheets cut from a C130 airplane and then transformed in the shape of the test bar samples for further fatigue detection experiments. Bar samples have length, width and thickness of respectively 210 mm, 10 mm and 2 mm. Besides, thick aluminum plates of 110 X 100 X 5 mm³ dimensions with calibrated cracks along the middle of the plate of different depths and widths have been fabricated and tested by our SQUID system. After a study of the influence of the lift-off distance ranging from 0.5 to 10.2 mm, in order to obtain the higher amplitude of the SQUID signal for the Al samples exposed to the same AC excitation, we have worked with the lowest distance of 0.5mm. The same geometrical and electrical parameters have then been considered for the modeling process.

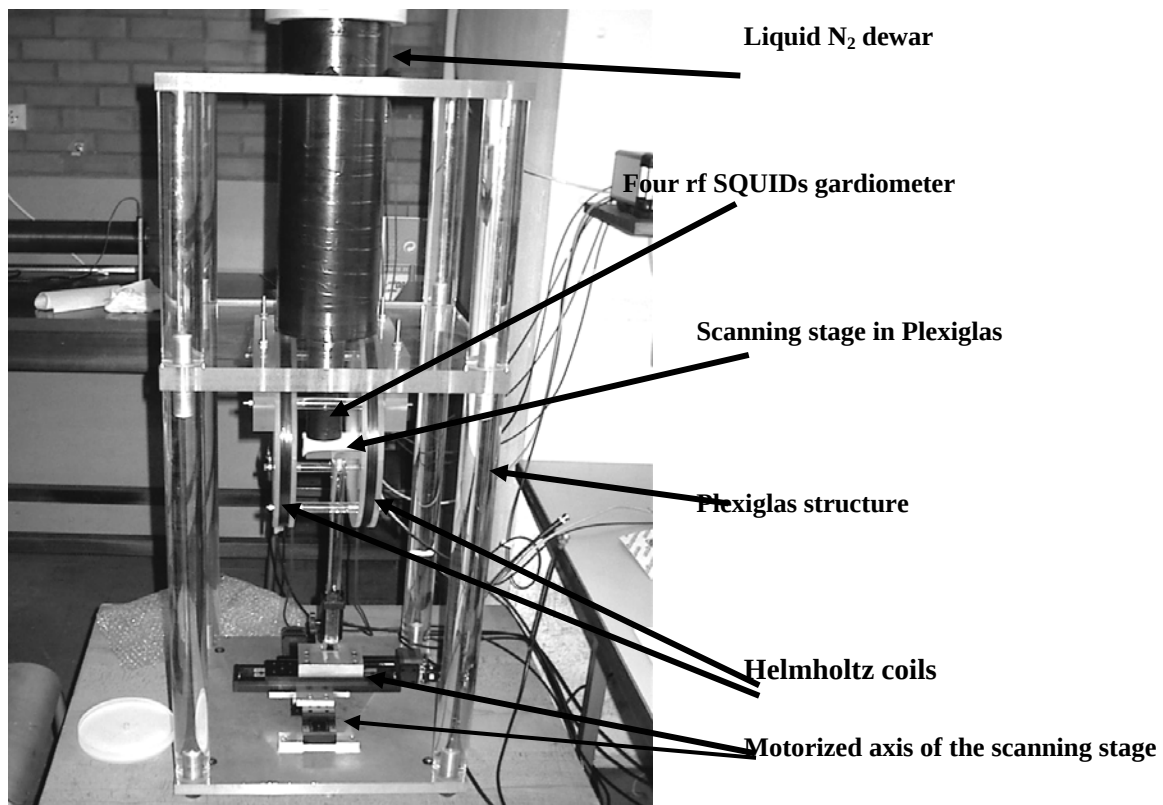


Figure 1: High Tc SQUID NDE setup.

3. Modeling

The excitation field B_{exc} is uniform and parallel to the sample. It creates the eddy currents that produce the induced magnetic field inside and outside of the sample. The z component of this field (measured by the SQUID gradiometer system) is computed at different distances from the surface of the sample. The current inside the plate, which varies in intensity with the skin effect, can be divided into sets of two pairs of current sheets of opposite directions (figure 2). The field that they create at an arbitrary

point can be computed simply by the law of Biot and Savart. So the sample cross section is divided into $n_{\max} * m_{\max}$ domains whose surface area is $dS = (c * a) / (n_{\max} * m_{\max})$ (figure 3). In these domains that we have considered to become small enough so that the currents are approximately uniformly distributed.

For the selected case of two arbitrary surfaces P and N (figure 4), we can evaluate the field at an external point M and then generalize this calculation to the whole cross section of different samples. Figure 5 shows the amplitude of the resulting calculated B_z component for a bar sample and for the different values of the lift-off parameter. The signals are quite symmetrical and their amplitude decrease with increasing lift-off. We have also considered a thick Al plate of $110 \times 100 \times 5 \text{ mm}^3$ dimensions with calibrated cracks of different depth and width along the middle of their upper surface. Figure 6 shows well the B_z and B_y values calculated for such a plate with a rectangular crack of 1mm depth and 1mm width. A lift off of 3.5mm has been used in these calculations in order to illustrate properly the signals of the edges of the plate and the signal in the center corresponding to the calibrated rectangular defect. It appears also that the field of the induced eddy currents is very small compared to the excitation field and therefore the initial approximation of the analysis is confirmed. In order to establish a data base of signals related to different defect shapes, the modeling process has also been adapted to model the forms as regular (figure 7) and irregular triangular cracks considering the symmetrical current densities. The signals obtained for such defects have shown clearly the correlation between the amplitude and form of the signals and the defects dimensions. Besides samples with two calibrated defects located at various distances have been also considered using this modeling method. The results have been correlated with measured signals and show the limit of spatial resolution of the set-up.

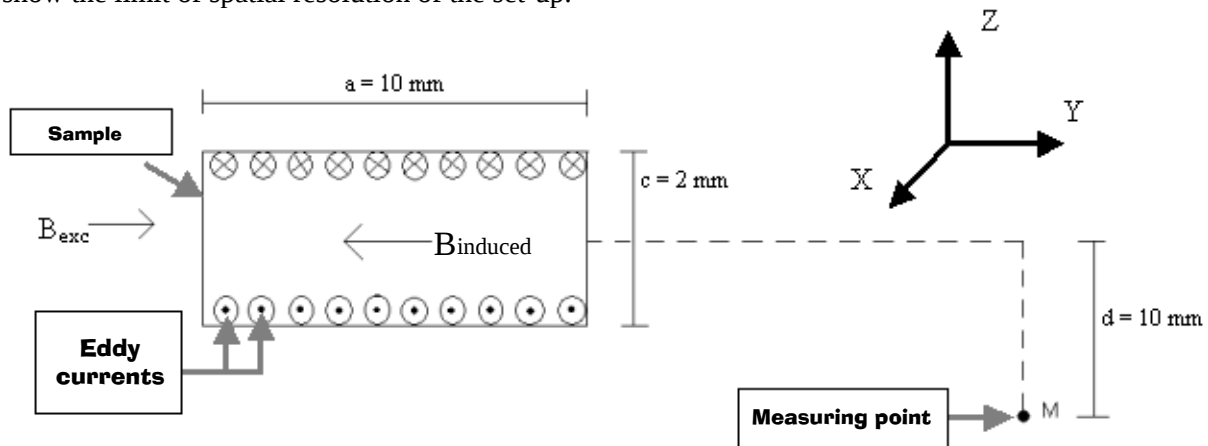


Figure 2 : Schematic of the modeling method.

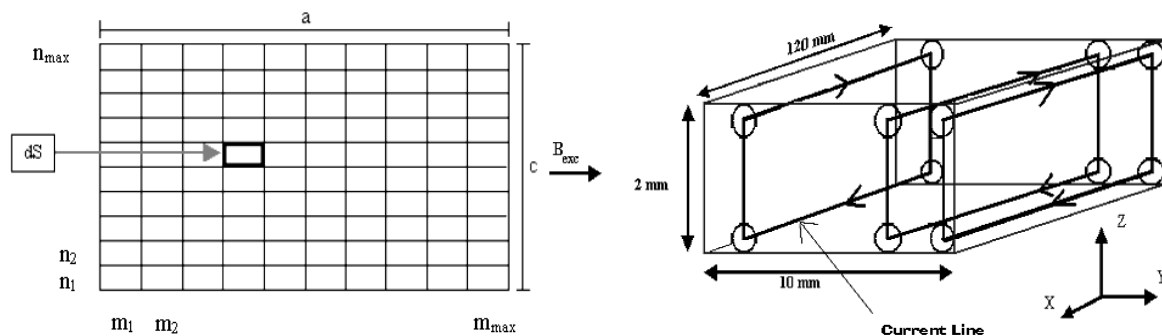


Figure 3: Schematic view of the sample cross section divided into $n_{\max} * m_{\max}$ domains with $dS = (c * a) / (n_{\max} * m_{\max})$ and the 3D view of the current density distribution.

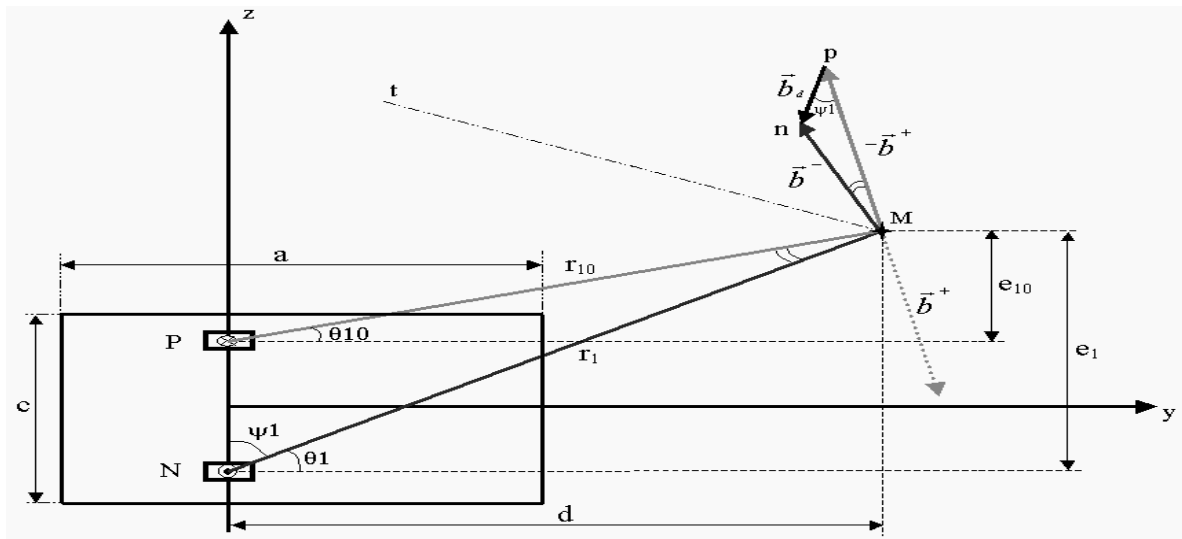


Figure 4: Determination of the magnetic field created at point M by two symmetrical domains of opposite currents.

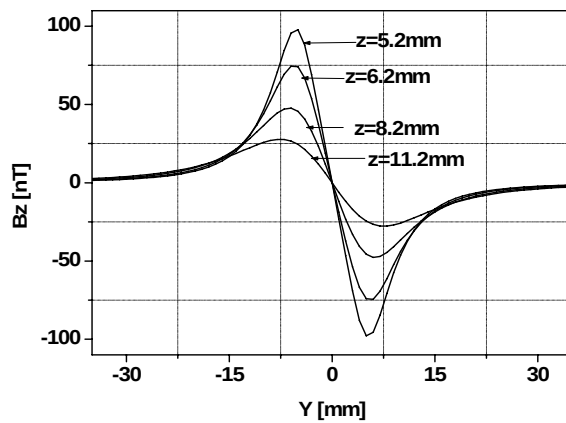


Figure 5: Bz values calculated for different distances above an aluminum bar sample.

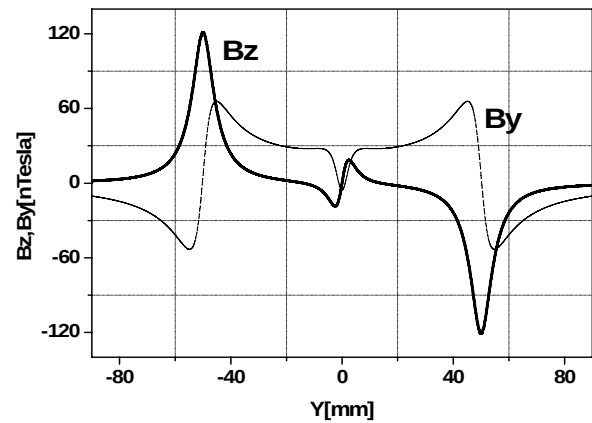
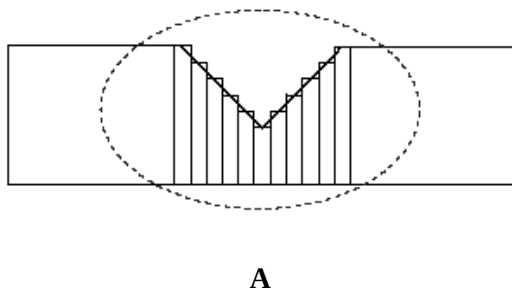
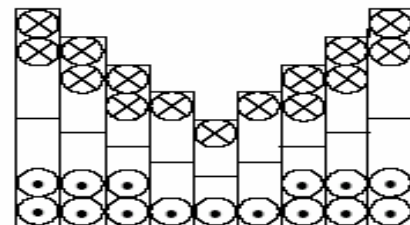


Figure 6: Bz and By calculated for a plate (110 X 100 X 5 mm³) with a rectangular crack of 1mm depth and 1mm width along its surface center.



A



B

Figure 7: Modeling process adapted to other defect forms as triangular (A), considering the symmetrical current densities (B).

4. Results

Using the RF SQUID experimental set-up, test samples of various shapes and with or without calibrated defects have been measured and the results have been compared with those obtained by our modeling method. As shown by figure 1, the samples are located on a scanning stage made of plexiglass in the center of the Helmholtz coils and this configuration allows to do a 50mm scanning along the Y axis with a step which can be as low as 0.1 mm. Figure 8 shows the amplitude of the calculated and measured B_z component for a plate ($110 \times 100 \times 5 \text{ mm}^3$) without any defect and located symmetrically on the stage with scanning of 50mm along Y axis. The correlation is quite good between measurement and modeling. In figure 9, three plates of same dimensions with rectangular cracks of 1mm width and three different depths (2, 1 and 0.5mm) have been measured. These measurements illustrate the ability of the system to detect properly the cracks smaller than 0.5mm depth. The peak to peak amplitude of the measured signal depend also strongly on the cracks width having the same depth (Figure 10). The comparison between the calculated and measured B_z component for a plate containing a rectangular defect of 1mm width and 1mm depth is shown on figure 11 and it shows a good matching between the results.

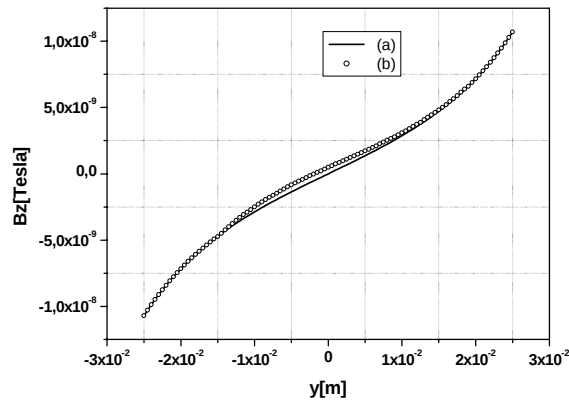


Figure 8 : B_z values calculated (a) and measured (b) for an Al plate ($110 \times 100 \times 5 \text{ mm}^3$) without any crack.

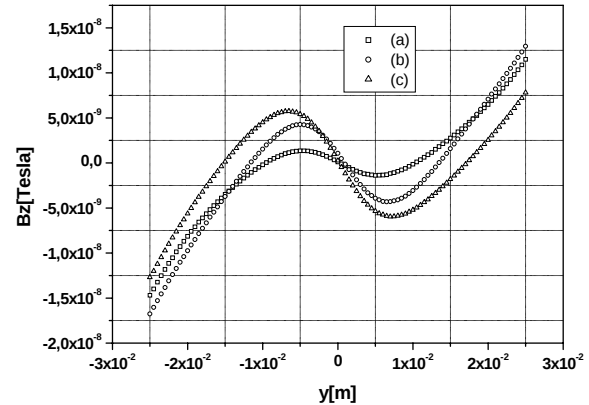


Figure 9: B_z values measured for Al plates ($110 \times 100 \times 5 \text{ mm}^3$) with cracks of 1mm width and different depths : (a) : 2mm, (b) : 1mm et (c) : 0.5mm.

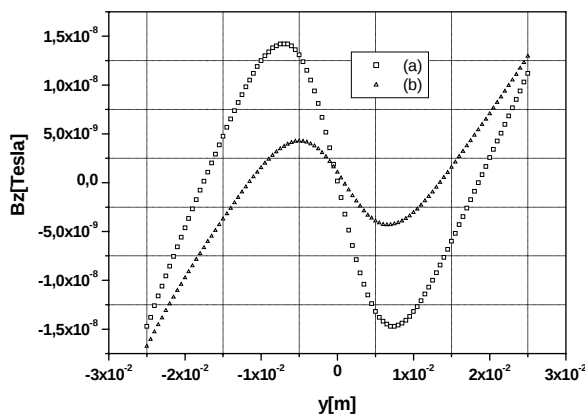


Figure 10 : B_z values measured for an Al plate ($110 \times 100 \times 5 \text{ mm}^3$) with a crack of 2mm depth and different widths (a) : 2mm, (b) : 1mm

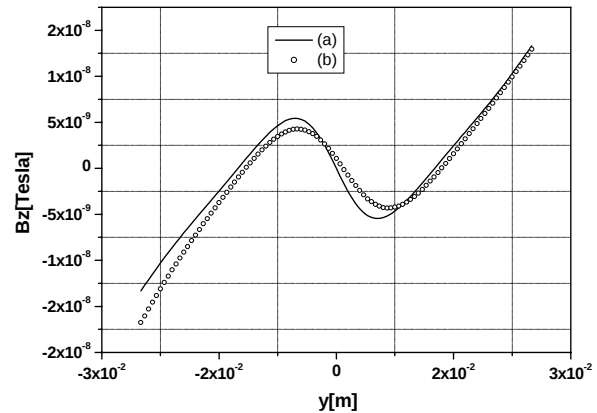


Figure 11 : B_z values calculated (a) and measured (b) for an Al plate ($110 \times 100 \times 5 \text{ mm}^3$) with a crack of 1mm width and 1mm depth.

5. Conclusions

The RF SQUID NDE experiment has been set up successfully in our laboratory. Preliminary results show that rectangular cracks as small as 0.5 mm depth and 1mm width can be detected in aluminum samples. Other tests are in progress to optimize the experimental conditions and to show the possibility of detection of smaller-sized flaws and also fatigue effects. The modeling technique which has been developed has proven an efficient, flexible and simple method, based on an analytical approach, to calculate the magnetic field created by the induced eddy current in a conducting sample at different distances from its surface. This modeling method has allowed to obtain results on defects of various shapes and even multi defects structures in a few minutes. The modeling results correlate well with the measured data obtained in an unshielded environment.

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