Non Destructive Evaluation of Advanced Composite Materials for Aerospace Application Using HTS SQUIDs

C. Bonavolontà, M. Valentino, G. Peluso, and A. Barone

***Abstract*—The main advantage of a HTS SQUID magnetometer in NDE applications is represented by its unrivalled magnetic flux sensitivity down to very low frequencies, which allows the detection of weak magnetic field variations due to defects also in materials characterized by a very low electrical conductivity. The imaging obtained by means of the magnetic flux variations can be an useful technique for an easier interpretation of SQUID magnetic responses getting along without post-processing algorithms and independent of the operator. Therefore, the SQUIDs NDE system output is compatible with the other conventional non destructive testing equipment for data fusion of aircraft inspections.**

***Index Terms*—CFRPs, eddy current testing, NDE, SQUIDs.**

I. Introduction

COMPOSITE materials, specifically Carbon Fiber Reinforced Polymers (CFRPs), offer superior mechanical properties such as high specific stiffness, high specific strength, corrosion resistance and fatigue resistance [1]. CFRPs are applied in aircraft and space structures which require light-weight design such as flaps, slats, spoilers, elevators etc. Advanced composite as CFRPs have been increasingly applied in aerospace structures because of their suitability for the production of complex-shaped components with reduced manufacturing time [2], [3].

However, due to low interlaminar strength, fiber composites are susceptible to delamination during their lifetime. CFRPs are able to absorb the energy of impact thanks to the presence of a polymeric matrix that distributes the energy in the material. In this way a low velocity impact does not produce a perforation but delaminations between the layers with no visible surface manifestation. The presence and the growth of delamination may cause severe stiffness reduction in the structure, leading to a catastrophic failure.

Due to the high probability of damaging composite materials during their manufacture, service and maintenance, it is required to detect, and evaluate the various types of damage caused by both static and dynamic loads using adequate predictive methods. Even if Non Destructive Evaluation (NDE) offers a variety of diagnostic methods such as laser-generated ultrasound [4], air-coupled ultrasounds [5], pulse echo ultrasounds [6], sherarography [7], X-ray refractography [8], they are often not entirely adequate to detect subsurface flaws and delaminations inside fiber reinforced plastic components because of their limitation in terms of accuracy, sensitivity, repeatability of the signal and sometimes difficulty of calibration.

In NDE applications, one of the widely used electromagnetic techniques is Eddy Current testing using induction coils. Generally, when it is applied to a composite [9], it shows a reduction of sensitivity to detect deep flaws because of the low electrical conductivity ($\sim 10^5\ \mathrm{S/m}$) of such materials and high sensitivity of the coil to lift off variation.

In the last twenty years, the high-$\mathrm{T_c}$ SQUID has become a promising alternative as an Eddy Current sensor. Thanks to its high magnetic field sensitivity and its ability to function down to zero frequency it can detect much deeper defects than traditional eddy-current sensors. Moreover, the wide dynamic range enables the SQUID to maintain its high sensitivity in the presence of harsh magnetic field noise, i.e. industrial plant, so that it is possible to monitor also the very low magnetic field variations induced in the fiber reinforced composites [10]–[13].

In this work magnetic imaging for NDE of composite material using a SQUID-based Eddy Current technique is presented. An alternative representation of the SQUID response is proposed to simplify the localization of damage in composite materials during their inspection independently of the operator. A comparison between the conventional Eddy Current output and the NDE SQUID based system is shown.

II. Experimental Set Up

The test samples $60 \times 60 \times 4\ \mathrm{mm}$ CFRP specimens with a multi-layer stacking sequence ($[(0/90), \pm 45]_{\mathrm{S}}$), are based on an epoxy-matrix (HFM 934) reinforced with a T400 carbon fibers content of 55% by volume, fabricated by hand lay-up and autoclave curing. The test specimens were damaged using a drop weight tower machine, having an hemispherical steel indenter with a diameter of 12.7 mm, the impact energy ranging from 0.14 J to 9 J.

The NDE prototype realized at CNR-INFM Coherentia laboratory is based on the dc HTS SQUID magnetometer characterized by a slew rate of $10^3\ \Phi_0/\mathrm{s}$ (at 1 kHz) a wide bandwidth (from dc to 26 kHz), a broad dynamic range (130 dB) and an high magnetic field sensitivity in unshielded environment (0.3

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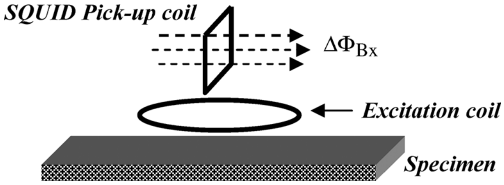

Fig. 1. The zero magnetic field probe set-up. The SQUID pick up coil is placed on the bottom of the dewar at 77 K at the position of the excitation coil center located outside the cryostat.

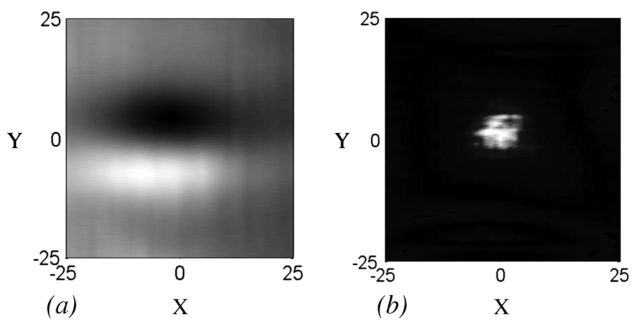

Fig. 2. (a) Image of magnetic field Bx in scanning direction (Y); (b) image of the magnetic field flux variation $\Delta\Phi$, of 4 mm thick CFRP sample after an 5 J impact.

$\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at 1 kHz). The signal of the SQUID output channel is filtered by a pre-amplifier electronics to avoid the signal aliasing during the analog to digital conversion. Then the signal is synchronously demodulated by a dual channel lock-in amplifier and is acquired by a 16 bit Digital to Analog Converter (DAC) at a rate of 6 points/mm. The data acquisition and the X-Y scanning table are software controlled. The test sample is placed at 2 mm distance from the excitation coil (a circular coil with the diameter of 5 mm and 20 windings) that is fed with an ac current of 5 mA rms at the frequency of 15 kHz. Moreover, the stand off between SQUID and sample surface is about 8 mm. The balancing of the probe is realized by using a double axis non-magnetic alignment stage, with a minimum step of 0.05 mm, affixed underneath the cryostat. The stage allows to align the center of the excitation coil in correspondence of the SQUID pick-up coil as shown in Fig. 1. The latter is orthogonal to the excitation coil plane so that only the in plane component of the magnetic field is measured. This configuration allows us to obtain a zero magnetic field probe, that is the SQUID measures a constant value of the magnetic field until a defect is detected during the sample scan. The probe calibration on CFRP material gives a zero magnetic field amplitude of -80 dB.

III. Results and Discussion

In Fig. 2(a), the magnetic field image of the damaged sample, impacted at 5 J, is shown. The distribution of the magnetic field induced in the sample is characterized by a dipole like image, which represents the damaged area after the impact. The magnetic field imaging due to the SQUID NDE prototype could be replaced by the magnetic flux imaging (Fig. 2(b)), which represents the variation of the magnetic flux measured by the SQUID magnetometer. Moreover, the magnetic flux imaging shows the defect as a white spot with shape and dimension comparable

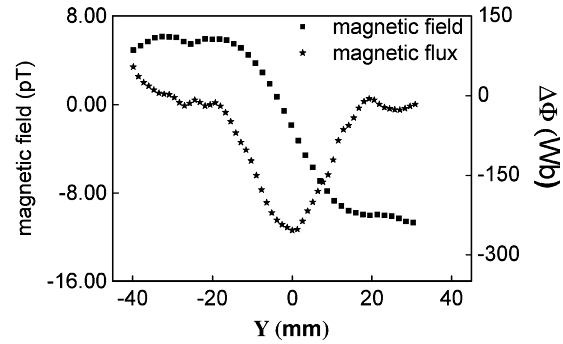

Fig. 3. Comparison between the lines scan across the center of the defect, magnetic field (square) and the normalized magnetic flux (stars).

with the damage detectable on the back side of the sample. The NDE system based on SQUID used in this work acquires at the same time both the magnetic field and magnetic flux of the damaged specimens.

Taking into account the Faraday law, the magnetic flux variation is related to the magnetic field variation by the following equation:

$$\Delta\Phi = \frac{\Delta B}{\Delta x} \cdot v \cdot A \cdot \Delta t \tag{1}$$

where $v(5 \cdot 10^{-3}\ \mathrm{m/s})$ is the constant speed during the acquisition, $A(8 \cdot 10^{-6}\ \mathrm{m}^2)$ is the SQUID pick-up coil area and Δt (10 s) is the data acquisition time. The above equation demonstrates how the magnetic flux variation is related to the spatial variation of magnetic field measured by the SQUID sensor.

Moreover, some considerations could be done observing the single lines scan across the defect as shown in Fig. 3.

In correspondence of the defect, the magnetic field signal is characterized by an inflexion while the magnetic flux has a minimum. It could be noted that in the magnetic field imaging the inflection can give information about the presence of the defect, but it is not easy to localize it. Instead, in the flux magnetic field representation it is possible a spatial localization of the defect and the flux variation is directly linked with the dimension of the damage. To test the magnetic flux response a comparison with the imaging obtained using Eddy Current with induction coil (Rohmann ELOTEST B300 and an absolute probe working at 580 kHz) has been performed. In Fig. 4 the maps related to the virgin and damaged samples are shown.

In the case of the virgin and 9 J impacted samples both the techniques obtain the same results, while in the case of very low impact energy (1.8 J) the SQUID response detects a damage, in contrast to the conventional eddy current technique. It could be noted that at 1.8 J impact energy the front and back surface of the specimen is undamaged, so that the damage is represented only by the internal delamination. As it is known delamination is due to the debonding of the composite layers which produces a variation of the fiber-layer position, and consequently, a variation of the fiber electrical resistivity. It has already demonstrated that even if this effect produces a low variation of the induced magnetic field, it can be detected by SQUID sensors [15], [16]. Ultrasonic tests performed on the sample impacted at 1.8 J demonstrate that only intra-layer defect is present in the

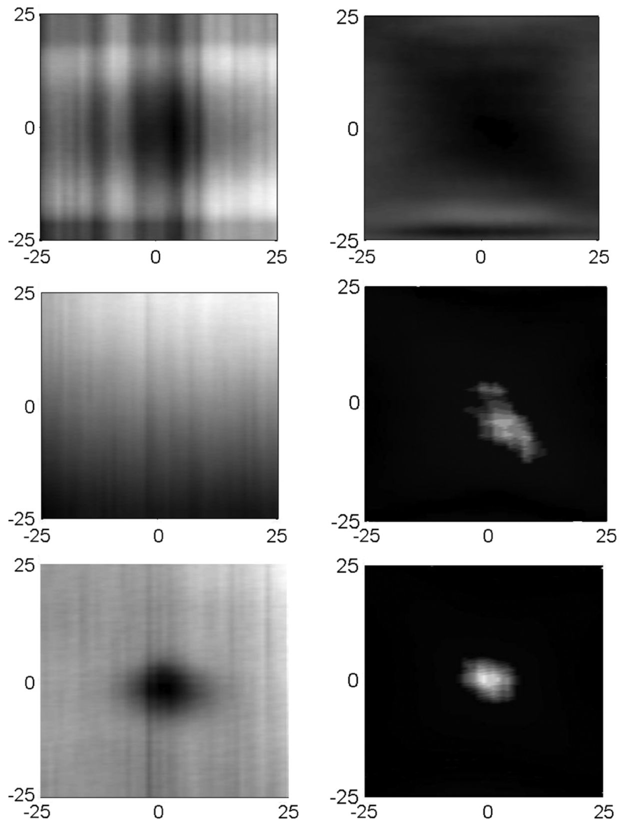

Fig. 4. Comparison between the EC responses (left column) and magnetic flux imaging (right column); from the top to the bottom the virgin sample, 1.8 J and 9 J impacted sample are shown, respectively. The in plane scan direction is along the vertical direction of the figures.

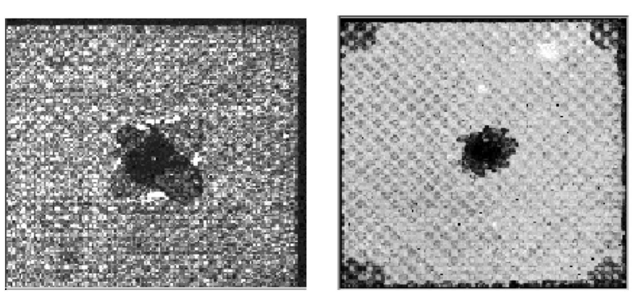

Fig. 5. Left and right are the ultrasounds imaging of the 4 mm thick samples impacted at 1.8 J and 9 J, respectively [14].

sample. Ultrasonic imaging for the CFRPs impacted at 1.8 J and 9 J are shown in Fig. 5.

It could be noted that the imaging obtained using the magnetic flux imaging is comparable with the image due to ultrasounds inspection. It means that the Eddy Current based on SQUIDs sensor using the magnetic flux imaging representation can compete with the conventional ultrasonic technique that are already used in the NDE investigation of CFRPs.

Moreover, the imaging of Fig. 4 shows that EC measurements are limited not only in the case of low energy impact but also to test the integrity of virgin sample. The latter is due to the comparable dimension of the map area with the specimen dimensions (edge effect). Therefore, the EC virgin sample map (Fig. 4 left top) is not an uniform image but is characterized by white stripes due to roughness of the surface and the edge effect.

TABLE I
INDENTATION AND THE DELAMINATED AREA VALUES

Energy (J)	**Indentation (mm)**	**Delaminated area (mm^2)**
1.8	0.03	42
5	0.15	195
9	0.20	2250

This results demonstrate that the SQUID magnetic flux imaging is more efficient than the conventional EC inspection technique on the CFRPs. In the SQUID flux imaging representation the edge effects are less remarkable than in the conventional EC. Moreover, the NDE SQUID system image shows a high sensitivity to the damage even at very low energy. The maps in Fig. 4 show that the flux imaging allows to detect the dimension and the location of the intra-layer damage even if the specimen appears undamaged at naked eyes. It could be noted that the larger the indentation on sample surface, more defined is the white spot on the magnetic flux image. As a consequence, the image of the delamination at 1.8 J impacted sample has not a well defined shape. This effect is not due to the technique but to the real characteristics of the damage. The value of the indentation and the delaminated area for the samples impacted at 1.8 J, 5 J and 9 J are shown in Table I.

It could be noted that the roughness of the CFRP material surface is often comparable or greater than the indentation value so that it is very difficult to detect the signal due to the impact with respect to the electromagnetic noise due the surface roughness.

The improvement that the SQUID magnetic flux imaging offers is represented by the good damage definition that is comparable with the ultrasounds imaging technique but better than the EC conventional technique using induction coil. Moreover, respect to the widely used Ultrasonic techniques, in which a coupling medium is required, the SQUID system guarantees a contactless inspection preserving an high magnetic field sensitivity to detect internal defects.

IV. CONCLUSION

In this work a NDE Eddy Current system prototype based on HTS dc SQUID magnetomer designed for testing of carbon fiber composite material has been presented. The imaging of damaged composite specimens obtained using the SQUID based prototype show that the magnetic flux imaging provides information about the localization and the dimension of the defect even if it is not visible to naked eyes. It is interesting to point out that the NDE SQUID based system detects an impact defect obtained with an energy of 1.8 J where the conventional EC fails. The SQUID magnetic flux offers an image of the damage better than or comparable to the imaging of the conventional NDT techniques and independent of the operator. Thanks to this characteristics the NDE system output can be used to deliver a data fusion with other techniques.

Future work is focused on the development of a new NDE HTS digital SQUID system based on 2nd order gradiometer including a cryo-generator system [17].

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