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Characterization of the damage process in GLARE® 2 using an eddy current technique based on HTS-SQUID magnetometer

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Abstract
In this work an eddy current technique based on a HTS-SQUID (superconducting quantum interference device) is used to evaluate the relation between the magnetic field response and the damage process of one of the most promising fibre metallic laminates known as GLARE®. In particular the magnetic field response due to impact loading at energies ranging from 5 to 36 J has been detected. The magnetic field signal from GLARE® specimens in the presence of mechanical damaging is discussed according to a simple electromagnetic model.

1. Introduction

The development of a new generation commercial aircraft, Dreamliner B-7E7 and A380, has been influenced significantly by the introduction of new composite materials. The use of composite materials with superb strength-to-weight and stiffness-to-weight ratios guarantees substantial weight saving. In aircraft design, the structural weight has an extreme importance on flight performance, transport capacity and fuel consumption. This means that improved materials with high specific strength and excellent mechanical properties such as GLARE® (GLAss Reinforced) made of advanced high strength glass fibres [1] and aluminium alloy are required. GLARE® is a type of fibre metal laminate (FMLs) which represents a new class of material that combines the best features of the organic matrix composites and metals. They have been regarded as advanced composite materials characterized by superior damage tolerant properties, inherent resistance to corrosion and good fire resistance for safety improvements. This kind of composite materials could be used to make cargo areas, floor applications and fuselage skin. Moreover, they can be considered good alternatives to the conventional metallic alloy in the new generation of aircraft structure.

The massive consumption of composite materials motivates a high innovation in the quality control techniques. Conventional inspection is based either on visual inspection or one of the different non-destructive testing (NDT) methods. The most established NDT techniques are ultrasound and eddy-current inspection. Ultrasound is preferred to detect corrosion, bondline defects or flaws in composite structures, while eddy currents are used for fatigue crack detections [2]. Unfortunately, these methods show serious limitations in the case of the GLARE® laminate composite. Indeed, ultrasound fails because of the multi-reflections that can arise within the metallic sheets, producing multi-frequency responses which can cover the signals related to the defect, while the high surface deformation, characteristic of the metallic alloy, damps the coupling between the materials and the eddy-current conventional coil. Moreover, visual inspection is insufficient to distinguish simple deformation from the cracking of inaccessible metallic sheets.

In this work an apparatus based on a magnetic field sensor, SQUID (superconducting quantum interference device), is proposed. The advantages of this sensor with respect to the conventional coils, employed in the eddy-current methods, consist in a low sensitivity to lift-off variations (the magnetic field detected by the SQUID decreases as $r^{-3/2}$ against

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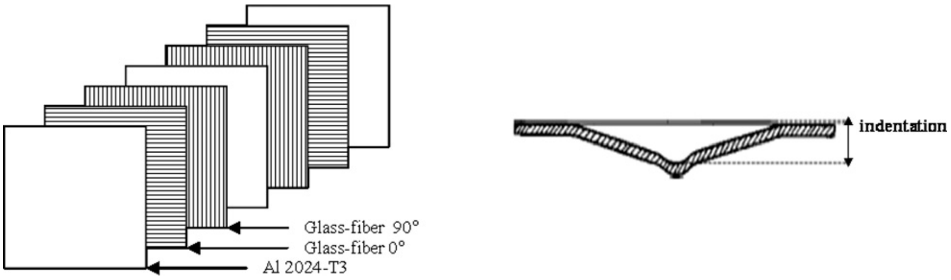

Figure 1. (Left) Schematization of the GLARE® 2 stacking sequence; (right) the profile of the impacted specimen due to the hemispherical steel impactor load.

the $\sim r^{-6}$ of the conventional coil response), the possibility to perform detection of deep flaws using low excitation frequencies and a very high sensitivity to the magnetic field variation less of 1 pT $\mathrm{Hz}^{-1/2}$ [3]. In this work the results obtained by a NDE system based on a SQUID magnetometer to detect impacts on GLARE® structures are reported. The correlation between the magnetic response of damaged specimens and the impact energy levels ranging from 5 to 36 J is shown. Moreover, with the aim of studying the mechanical behaviour of the fibre–metal laminate, the impacted area has been modelized and the results of the electromagnetic model have been compared to the experimental SQUID magnetic field measurements.

2. Experimental system and test samples

The experimental setup based on eddy-current techniques using a HTS dc-SQUID magnetometer was realized at CNR-INFM Laboratory in Naples.

The eddy-current probe used by the NDE system is a high-T_c dc-SQUID magnetometer, inductively coupled. The effective area of the SQUID pick-up coil is 81 mm^2; it is oriented to measure the in-plane component of the magnetic field, B_x or B_y. The SQUID magnetometer operates in a flux-locked loop (FLL) configuration working with a 3 dB bandwidth of 26 kHz. The field-flux transfer is 1.14 nT$/\Phi_0$ and the magnetic field sensitivity in an unshielded environment is 0.3 pT $\mathrm{Hz}^{-1/2}$ for frequencies above 100 Hz. Moreover, the SQUID has a slew rate of 10^3 Φ_0 s^{-1} and a dynamic range of about 130 dB. Eddy currents were induced on the test sample by a wire-wound circular coil with a diameter of 5 mm and 10 turns, realized by winding a copper wire of diameter 10 μm. The coil is fed by a current generator HP 3245 A, with typical operating current less than 20 mA in a frequency range of 1–26 kHz.

The output channels of the SQUID read-out electronics send the signal to a anti-aliasing filter during the digital conversion in the bandwidth of 30 kHz. Afterwards, the signal is synchronously demodulated using a dual-channel lock-in amplifier, locked at the frequency of the excitation current and set so that the modulation and phase of the magnetic field are acquired. The demodulated signals are converted into a digital signal using an analogue-to-digital converter with 16-bit resolution that ensures a signal dynamic range of 96 dB with amplitude up to ±1 V and stored on a PC. The non-magnetic x–y stage, used to move the test specimens under the coil, is controlled through software by a PC connected to an RS232 interface. The acquisition program is realized in the Labview® language and it is capable of controlling the x–y stage and acquiring the data in continuous mode. The scan speed ranges between 1 and 25 mm s^{-1}.

The GLARE® specimens, tested in this work, are made of three aluminium 2024-T3 layers, each with a thickness of 0.3 mm, bonded together by four unidirectional S2-glass fibre sheets, oriented at 0° and 90°, each with a thickness of 0.125 mm as shown in figure 1.

In this work, the test specimens, with dimensions of 150 mm × 150 mm × 1.32 mm, were impacted using a hemispherical steel impactor, 15 mm in diameter and 2.1 kg in mass, which struck the sample at the centre by a CEAST modular falling weight machine type MK3, equipped with a DAS 4000 data acquisition system. Different indentations were produced in the specimens by varying the impact energy U, which ranged from 5 to 36 J.

The impact produces a surface deformation characterized by an indentation, see figure 1 (right). The aluminium deformation has an ellipsoidal shape, as shown in figure 2 by a dotted line. Moreover, increasing the energy impact above 20 J, a part from the deformation, a crack in the bottom aluminium sheet occurs, while an impact energy up to 36 J produces a crack in the aluminium sheet located in the middle and on the surface of the laminate (figure 2). Therefore, in GLARE specimens the damage of aluminium layers begins on the layer furthest from the impacted side and only in the last stage appears on the surface.

3. Results and discussion

In figure 3 the signal responses of magnetic field amplitude related to the specimens impacted at 5, 10, 20 and 36 J, using the HTS-SQUID magnetometer, are reported. It could be noted that these magnetic signals have a minimum in correspondence to the maximum indentation ($x = 0$).

This is more evident observing figure 3 (right) where an enlargement in the range −5–5 mm around the maximum indentation is shown. The experimental data demonstrates that the minimum of the magnetic field decreases when the energy impact increases.

This result is achieved thanks to the high magnetic field sensitivity of the SQUID with respect to the high lift-off variation. Indentation measurement demonstrated that at 36 J a lift-off variation of 6 mm is produced. Typically, such

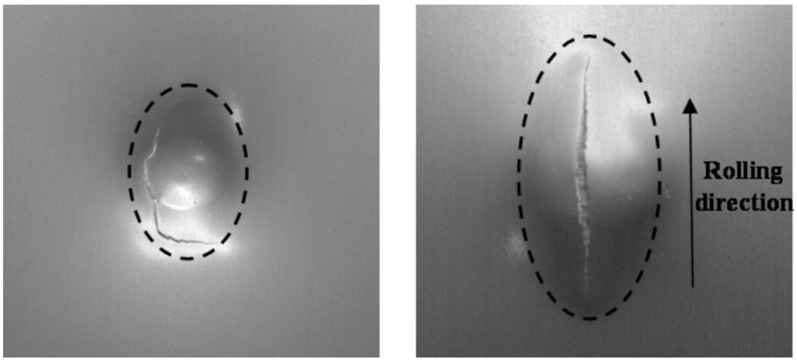

Figure 2. (Left) and (right) Cracks on the front and back aluminium layers, respectively, for a specimen impacted at 36 J. The dotted line represents the ellipsoidal deformation present on both sides.

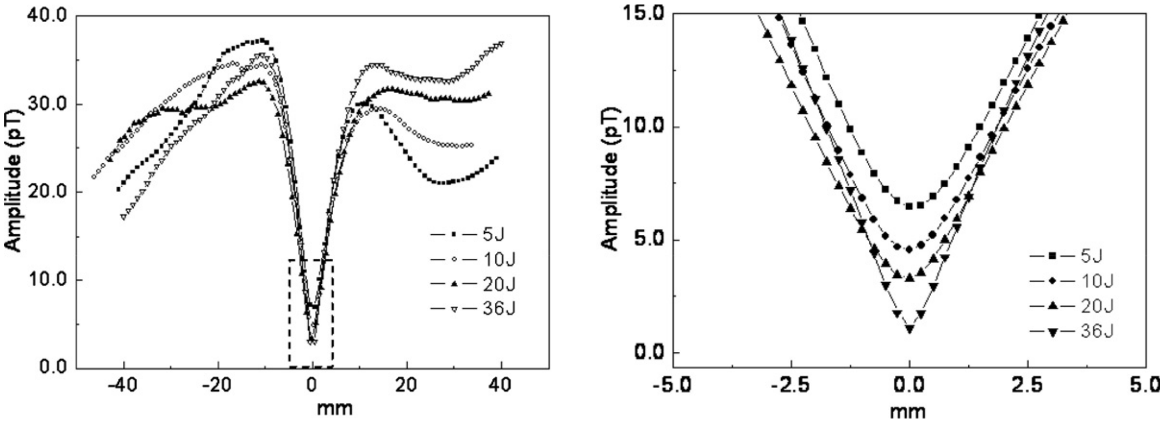

Figure 3. (Left) The amplitude of the magnetic field B_x versus the line scan displacement for the specimens impacted at 5, 10, 20 and 36 J. (Right) The enlargement of the B_x amplitude included in the rectangular area on the left.

a lift-off variation mismatches the coupling between sample and conventional eddy-current induction coil. Instead this limitation does not involve the SQUID magnetometer that is capable of detecting the magnetic field variation even if high lift-off variation occurs.

Typically, in the eddy-current testing (ECT), measurements are reported in a diagram, called the impedance plane or *Gauss plane*, to achieve an easier interpretation of the signals. In figure 4 the impedance plane representation of the SQUID magnetometer signals for samples damaged at 5, 10, 20 and 36 J are shown. The quadrature and the in-phase components of a single line scan, across the deformed area, are reported on the x axis and y axis, respectively. In this representation increasing the energy level changes the magnetic field trajectory.

In the impedance plane the signal related to the virgin sample appears as a spot centred at (0, 0) coordinates. On the other hand, when a specimen deformation is detected the signal is characterized by a trajectory due to the variation of the real and imaginary magnetic field component.

It could be noted that in figure 4 the signal related to the only deformed specimen (5 J) could be approximated as a straight line, while the signals related to the damaged samples 20 and 36 J are characterized by a more complex trajectory. The different trajectories between the deformed and the damaged sample signals means that increasing the impact energy changes the characteristics of the damage.

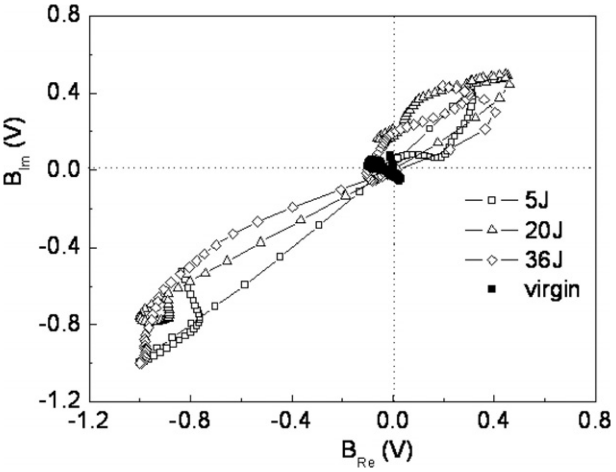

Figure 4. The impedance plane of the SQUID magnetometer response (B_x) changing the impact energy. The arrows show the range of the in-quadrature and in-phase component of the magnetic field SQUID output.

In particular, the rotation of the magnetic signal with respect to the reference axis ($X = 0$ and $Y = 0$) gives an estimation of the damage in the specimen. The rotation is measured as the angle that the curve forms with the x axis.

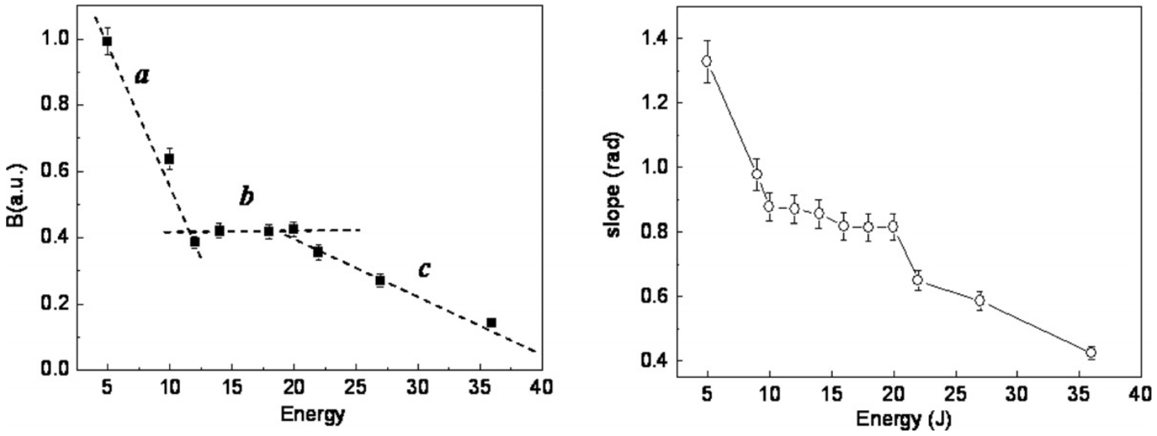

Figure 5. (Left) Minimum of the magnetic field amplitude (B_x) versus the energy impact. The value of bar error is 5%. (Right) Magnetic field $B_{\mathrm{Im}}/B_{\mathrm{Re}}$ ratio versus the energy impact.

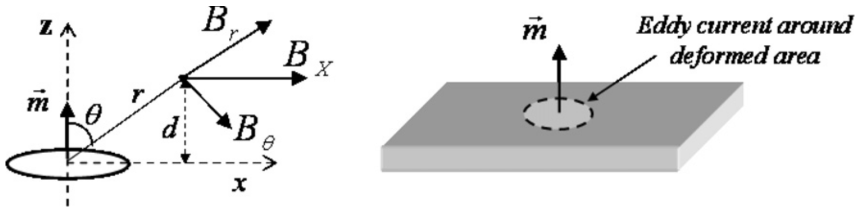

Figure 6. (Left) Magnetic field B_x generated by a circular coil with a magnetic dipole oriented along z axis. (Right) Magnetic field dipole produced by the circular eddy current around the deformed impacted area.

This angle is approximated by the slope of the curve calculated as arctan ($B_{\mathrm{Im}}/B_{\mathrm{Re}}$).

Since in previous work, it was demonstrated [4] that the minimum of the magnetic field signal can be considered as a parameter to distinguish in GLARE® specimens the defects due to the different impact energy levels, the same result can be achieved using as parameter the slope of the curve in '*Gauss plane*' representation. In figure 5, the minimum and slope of the magnetic field signal are reported.

The relation between the parameters and the energy impact is characterized by three different trends. The first, named a, includes the energy range from 5 to 12 J. In this range the magnetic field response decreases, increasing the energy of impact. In the range b, between 12 and 18 J, a plateau appears, and the magnetic signals do not change significantly. It is interesting to note that, in this range of energy, the sample deformation acquires an ellipsoidal shape, as is demonstrated by a visual inspection. The major axis of the ellipsoid coincides with the aluminium rolling direction and it is orthogonal to the measured magnetic field component B_x. Then, the values in the c range shows a further decreasing of the magnetic field signal.

It is important to note that both graphs of figure 5 show a plateau, in correspondence to the energy range 10–18 J, and an abrupt decreasing of the slope in the range 5–12 J and 20–36 J.

To understand the experimental results it is needed to consider that the magnetic field response, detected by the SQUID magnetometer, is due to the overlapping of two effects: the lift-off and the electrical conductivity variation. The first effect is produced by the deformation of aluminium sheets due to impact loading. In particular, increasing the indentation of aluminium layers, the distance between the sample and the HTS-SQUID magnetometer increases and the detected magnetic field is reduced. Moreover, the variation of the electrical conductivity is due to the failure of the aluminium layers due to an energy higher than 20 J. A crack in the aluminium sheet produces a reduction of the electrical conductivity so that a decrease of the magnetic field signal is produced.

It is important to note that in the energy range from 10 to 18 J, the magnetic field parameters do not change considerably, even if a lift-off variation (about 1.5 mm) tends to reduce the detected SQUID magnetic field intensity.

An explanation of this result is suggested, as follows. The magnetic field component B_x, detected by the SQUID magnetometer, on the impacted area can be considered as generated by a magnetic dipole, $m = IA$ where I is the eddy current (considered constant in an undamaged sample) and A is the sample deformed area. The magnetic field components and the magnetic dipole $\mathbf{m}$ oriented along the z axis are shown in (figure 6 (left)).

Considering the magnetic field components, B_r and B_θ, calculated at distance r in cylindrical coordinates, the amplitude of the magnetic field B_x is:

$$B_x = B_r \sin\theta + B_\theta \cos\theta = \frac{\mu_0 m x d}{4\pi (x^2 + d^2)^{\frac{5}{2}}}. \qquad (1)$$

For each energy, the value of $\mathbf{m}$ has been calculated fitting the experimental magnetic field signal using equation (1). In figure 7 an example of curve fitting related to the magnetic field signal of the 5 J impacted sample is reported.

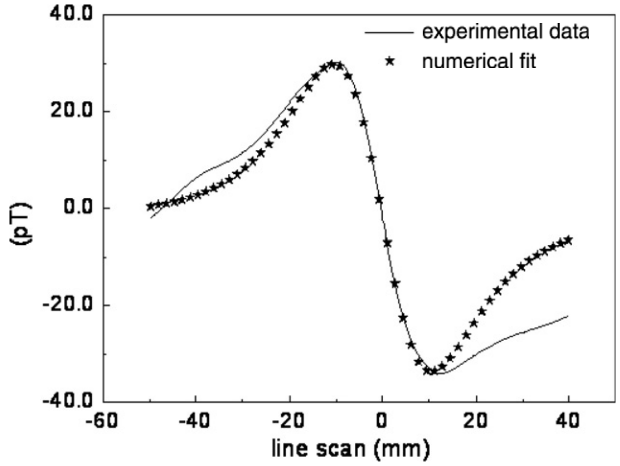

Figure 7. Curve fitting using equation (1) in the case of a sample impacted at 5 J.

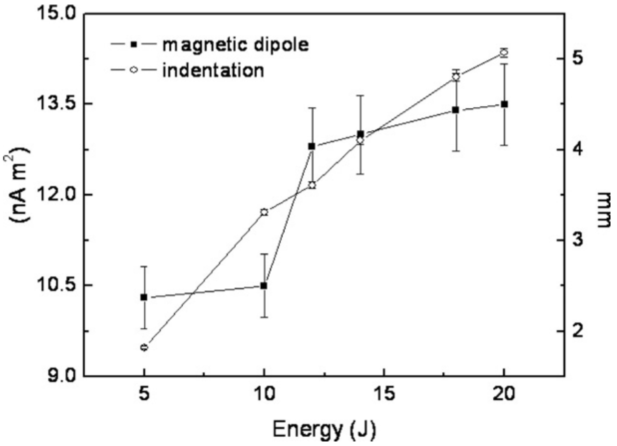

Figure 8. The magnetic dipole (left), evaluated using equation (1), and the indentation measured on each specimen (right), versus the impact energy.

Table 1. The magnetic dipole and the deformation area versus impact energy level.

Energy (J)	Magnetic dipole (nA m^2)	Deformed area (mm^2)
5	10.3	19.6
10	10.5	37.7
12	12.8	49.4
14	13.0	56.5
18	13.4	55.0
20	13.5	103.6

The discrepancy between the curve fitting and the experimental data, visible at the end and beginning of the curve, is due to the sample holder clamp deformation, located far from the impacted area. This effect is not considered in equation (1) and in our opinion it does not clash with the model since the signal of the indentation area is represented only by the inflection of the curve. The latter, in fact, as shown in figure 7, is fitted by equation (1) to a good approximation.

The values of the magnetic dipole **m**, and the deformed area versus the energy range 5–20 J, are reported in table 1. The first is calculated as a fitted parameter, while the second is measured by ultrasound inspection.

From the data reported in table 1 it could be noted that the increase in magnetic dipole intensity corresponds to an enlargement of the deformation area. In particular between 10 and 12 J there is an abrupt increasing of the magnetic dipole intensity. This result is due to the fact that the deformation for energy above 10 J is extended much more in the metal rolling direction, producing on the sample an ellipsoidal shape. Since the SQUID magnetometer measures the magnetic field component B_x generated by the eddy current that flows in the rolling direction, the detected signal increases.

Moreover, in the range 12–20 J, increasing the deformed area there is an improvement of magnetic field dipole intensity that compensates for the reduction of the signal intensity due to the indentation improvement. This statement is better represented by figure 8, where the variation of the magnetic field dipole and the indentation versus the impact energy are shown.

It could be noted that for energies between 5 and 10 J the variation of indentation prevails on a low enhancement of magnetic dipole intensity, while for energies between 12 and 20 J, the magnetic dipole intensity increases much more than the indentation. Therefore, in the range 12–20 J, the plateau arises from the compensation of the magnetic dipole intensity with respect to the lift-off variation.

In the range of impact loading from 20 to 36 J, cracks appear in the aluminium layers. The latter produces a decreasing of the electrical conductivity of the material and an increasing of the indentation. Therefore, the approximation of the experimental signal with a magnetic field produced by a magnetic dipole is no longer appropriate.

4. Conclusions

The eddy-current technique based on the HTS-SQUID magnetometer has been applied to detect different damage in fibre–metal laminates such as GLARE®. The experimental results demonstrate that it is possible to distinguish in this composite material a damage process characterized by different stages.

The presence of a plateau in the correlation between the magnetic field and the energy impact reveals that the SQUID magnetic field response is very sensitive to the extension of aluminium layers' deformation even when high lift-off variation occurs. In particular, by using an electromagnetic model it has been demonstrated that in the range 12–20 J the lift-off signal intensity variation is compensated by the improvement of magnetic field dipole intensity due to aluminium layers' deformation. These experimental results confirm the applicability of the eddy-current technique based on the HTS-SQUID magnetometer to study the mechanical properties of the fibre–metal laminate during mechanical stress.

Acknowledgments

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