Eddy Current Nondestructive Evaluation Using SQUID Sensors

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Introduction

Eddy current (EC) nondestructive evaluation (NDE) consists in the use of electromagnetic techniques through which the inspection is carried out by detecting magnetic anomalies in the material under examination. The testing activity was focused on the inspection of aluminium alloy material samples. The technique used is the magnetic flux variation detection by acquisition of a sensor signal proportional to such variation. Measurements were performed through an innovative approach based on superconductive material sensors (SQUID magnetometry). EC images were created by scanning the material sample and processing the sensor signals detected during scanning using a custom software for eddy EC generation.

Eddy Current NDE based on Superconducting Quantum Interference Device (SQUID)

SQUID sensors

Many metals and metal alloys at very low temperature (few °K or few fractions of a °K) become superconductors: their electrical resistivity drops abruptly to zero. This phenomena cannot be interpreted on the basis of classical physics but only resorting to quantum mechanics (theory of Bardeen, Cooper and Schrieffer). The temperature at which a material becomes a superconductor is known as critical temperature. In a circuit made of superconducting material, the current can circulate without energy dissipation: once started, current flow can be maintained without the action of any electromotive force. Superconducting materials possess peculiar properties: if they are immersed in a magnetic field, provided it is lower than a given critical value, they eject the magnetic field itself (Meissner effect). If the magnetic field is higher than the critical value, the material stops to be superconducting even if its temperature is lower than the critical value.

A SQUID is a magnetic flux detector having the topological structure of a superconducting ring interrupted by two weak links (Fig. 1). One relevant property of a superconducting ring is that the magnetic flux inside the ring is quantized in multiples of the flux quantum $\Phi_0 = h/2e = 2.07 \times 10^{-15}$ Tm^2 [1].

Furthermore, when an externally applied magnetic field is increased or decreased, a superconducting current circulates around the ring to maintain the value of the flux within the ring invariant. This is possible through a feedback control of the flux. If the continuous superconductive path of the ring is broken by incorporating a weak link (Josephson junction), the link reduces the strength of the circulating current for a given applied flux [2]. If an external magnetic field is applied, the SQUID reacts determining a variation of the incidental voltage on the SQUID (Fig. 2). Thus a measurement of the applied external magnetic flux is made possible trough the measurement of the incidental voltage on the sensor [1].

SQUID eddy current testing

In the comparison with traditional eddy current sensors, SQUID based sensors offer higher spatial resolution and greater sensitivity in a wide frequency range (D.C. to 1 MHz) which make them particularly suited for detection of surface, sub-surface and deep defects in conducting material. Rather bulky for certain specific applications a portable measuring system for the detection of defects in planar structures is a practical application of SQUID based NDE. Active noise compensation techniques such as electronic gradiometry, total field compensation and individual flux compensation allow SQUD based sensor to operate even in harsh environmental conditions. Moreover, due to flux-locked-loop electronics, these magnetometers work with a large dynamic range and high linearity. The advent of SQUIDs made of high critical temperature superconductive materials working at the temperature of the liquid nitrogen (77 °K) allowed to overcome the technical difficulties and the high cost related to liquid helium cooling systems. This represents fundamentals progress towards the realisation of a portable device.

A scheme of the EC NDE system based on SQUID sensors is shown in Fig. 3 [3, 4]. The operative temperature of 77°K is reached by liquid nitrogen-bath cooling using a specially designed fiberglass Dewar. The bottom of the Dewar cryostat has a window of 12 x 100 mm^2 with a thickness of 1 mm immediately under the position of the SQUID. Eddy currents are induced into the material sample by a double D shaped coil, shown in Fig. 4.

The geometry of the coil, allows for the zeroing B_z component of the magnetic field inside the gap between the two Ds. Under these condition, the SQUID gradiometric sensors detect a fraction of the magnetic field in the z direction when the presence of a defect in the material sample deviates the eddy current flow and accordingly determines a non zero magnetic field inside the gap of the 2 D inducing coil. The AC source is a programmable low-noise HP3245A waveform synthesiser. The alignment between the SQUID sensors and the coil is achieved moving the latter with a suitable X-Y displacement system placed just below the Dewar cryostat. The system used Tristan low-noise IMAG-3 Hoc SQUIDs. The outputs of two SQUIDs are electronically subtracted in order to have a gradiometric configuration. One sensor detects signal and noise, the other only noise. The SQUID electronics output is connected to an EG&G5210 dual channel lock-in amplifier, which demodulates the detected signal and provides the AC signal outputs with 6 Hz bandwidth. A newly designed non metallic X-Y scanning system, entirely in μ metal material, with a sub-millimetre positioning accuracy displaces the sample at 1 mm/s beneath the stationary Dewar cryostat. The motors are located 1.5 m away from the inspection area and are coupled to the positioning system by plexiglass rods. Both data acquisition and scanning system are computer controlled.

Eddy current imaging

In this section, images obtained from SQUID sensor EC scanning carried out are presented. Sensor data from scans are available as a 2D numerical array. Each row in the array contains the numerical values of the detected signal for each material interrogation point with constant step during one scanning line. The set of scanning lines makes up the entire X-Y scan. The 2D numerical array is normalised and images with 128 grey tones or pseudo colours are created using the Image Processing Toolbox of Matlab [5]. This software package allows for further image processing procedure in 2D and 3D. The creation of 3D images is realised by reporting the values of grey tone intensity in the 2D matrix on the z axis.

SAMPLE	SENSOR	STEP	AREA	GENERATOR
Al alloy sheet with central blind hole (control from the side of the defect)	SQUID $A_{eff} < 10$ mm^2	1 mm	X = 40 mm Y = 40 mm	I = 5 mA F = 277 Hz

Tab. 1 – Scan parameters; A_{eff} = effective area covered by the sensor.

Results from SQUID testing

A SQUID based EC scanning was carried out on a 3 mm Al alloy sheet with a blind hole of 6 mm diameter and 2 mm depth (Fig. 4). Testing was carried out from the defect side using the parameters reported in Tab. 1. The vertical component B_z of the detected magnetic field was utilised for image creation. In Fig. 5, 2D images in 128 grey tones obtained from the scan of the Al alloy sheet with circular blind hole are reported together with the indication of the excitation coil path. The blind hole acts as a current dipole lying on the surface of the sample, which represents a conducting half-space, and produces a field that emerges from the material surface on one side of the defect and enters on the other [6]. The EC images allow for the identification of the blind hole by means of two semi-circular areas with opposite orientation and grey tone intensity. The semi-circular area with higher grey tone values (white) represents the vertical component B_Z of the field emerging from the surface whereas the semi-circular area with lower grey tone values (black) represents the field entering the surface. The blind hole position in the sample plane is located at the centre of the two semi-circular areas, its diameter is related to the diameter of the semi-circular areas, and its depth can be related to the difference between maximum and minimum grey tone values in the two semi-circular areas: the higher the difference, the lower the blind hole depth. This difference can be visualised in the 3D images in Fig. 6 obtained by reporting the B_z value on the z axis.

Future work

Future work will concentrate on the development of the testing methodology using SQUID sensors. Sensor signal processing and image analysis will also be further developed.

References

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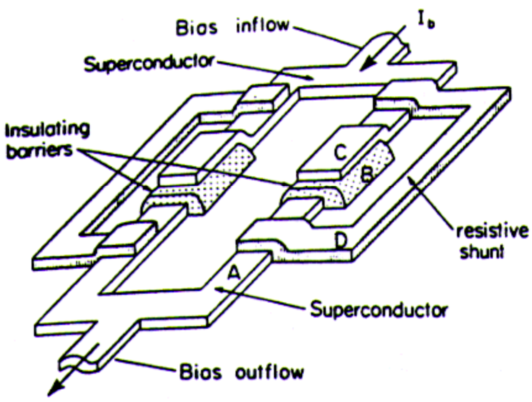


Fig. 1 – Schematic of a SQUID: A) superconducting material, B) layer of insulating material, C) another layer of superconducting material, D) layer of normal metal to provide resistive shunts across each insulating junction.

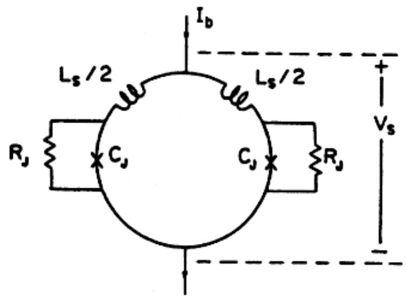


Fig. 2 – The equivalent circuit diagram of the SQUID.

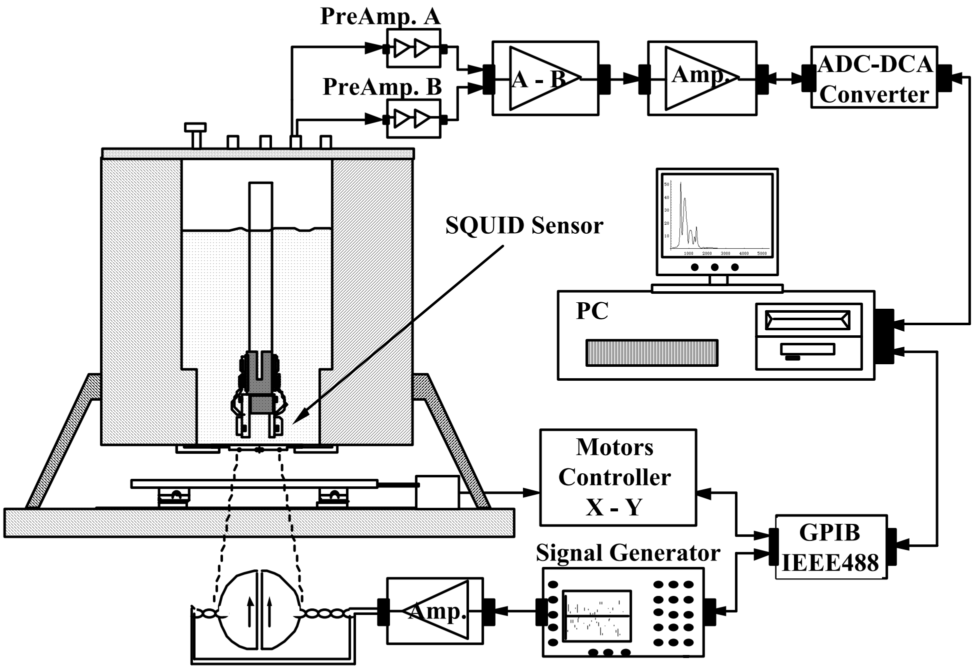


Fig. 3 – Scheme of the SQUID based EC NDE system.

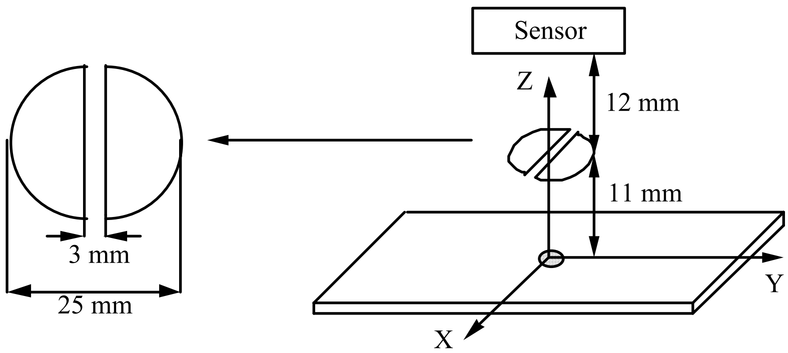


Fig. 4 – Details of the double D shaped coil and distances between SQUID, coil and sample.

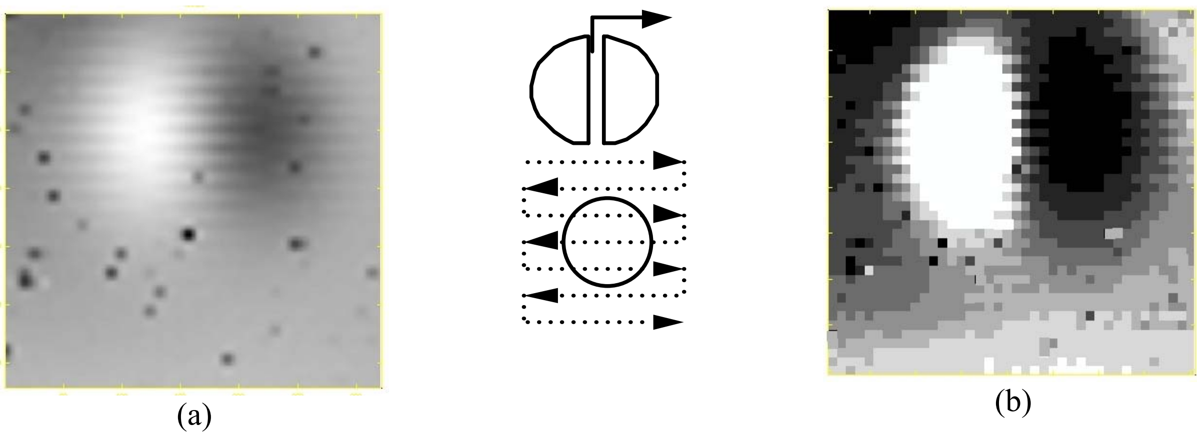
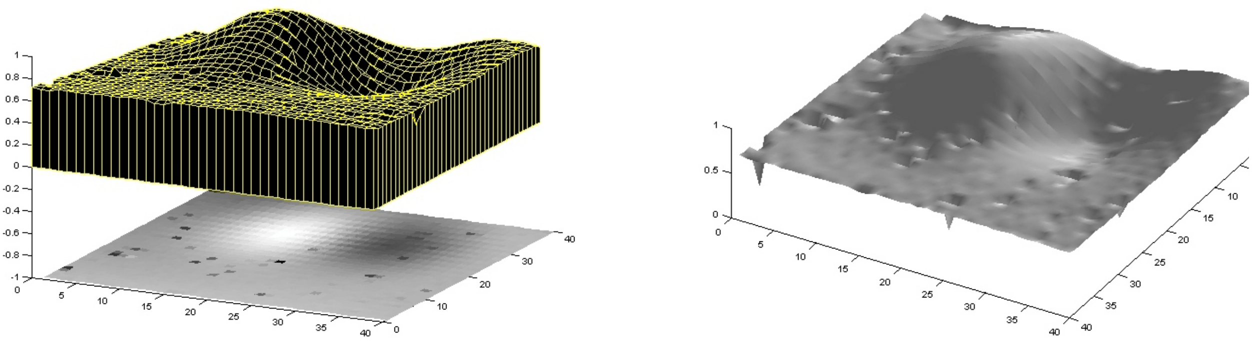


Fig. 5 – (a) Normalized 2D gray tone image and (b) contrast enhanced 2D image, with indication of the path of the excitation coil (center).



(a) (b)

Fig. 6 – (a) 3D wirenet representation combined with 2D gray tone images, and (b) 3D representations with pseudocolor graded surface.